WESTINGHOUSE ELECTRIC CORPORATION

AEROSPACE ELECTRICAL DIVISION

LIMA, OHIO

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SPACE ELECTRIC POWER SYSTEMS STUDY

PROGRESS REPORT - SECOND QUARTER

(February 8, 1962 to May 8, 1962)

CONTRACT NAS5-1234

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WESTINGHOUSE ELECTRIC CORPORATION

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F. C. Stump
Systems Engineer

N. W. Bucci, Jr., Mgr.
Systems Section

WESTINGHOUSE ELECTRIC CORPORATION
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SECOND QUARTERLY PROGRESS REPORT

(Reporting period: February 8, 1962 to May 8, 1962)

NAS5-1234

Report Prepared By:

F. X. Dobler
C. L. Doughman
R. C. Fear
G. E. Gerecke
M. A. Geyer
L. L. Hire
D. E. Krummel
J. W. Ogden
D. D. Pollard
W. A. Shilling
O. G. Smith
F. C. Stump
E. F. Swiderski
L. L. Tipton

27879

SUMMARY

The general objective of the study program is to develop parametric data for the generation, control, conversion and transmission of electric power for space vehicles. The coolant temperature for the generator is between 500°F and 1500°F. The ratings to be studied are between one and ten megawatts. Voltage levels for the system are between 5000 and 50,000 volts d-c.

This report presents the technical data developed during the three-month period ending May 8, 1962.

In compliance with the objectives of the study program, the technical information compiled during this period covers the following items:

1. Generator designs for two, five, and ten megawatts over the voltage, temperature, and speed range.
2. Parametric data of generator weight and efficiency as a function of system rating.
3. Parametric data of weight and efficiency for electrical conversion and control devices as a function of system rating.

author

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1.0 OBJECTIVES OF THE STUDY

The objective of this program is to provide parametric data to aid in the study of practical electric power generation and transmission systems for use with electric propulsion engines. This objective is divided into four major parts:

1. Develop parametric data for electric power systems.

2. Prepare the parametric design data in a form readily applicable for use in the complete analysis of power conversion systems.

3. Perform detailed design studies and prepare preliminary designs for three of the most promising electric power systems concepts resulting from the parametric data.

4. Summarize the required research and development areas for the electric system. This summary will recommend programs to cover the areas in which additional effort is required to assure the successful design and development of a flight prototype system.

2.0 REQUIREMENTS AND SCOPE OF THE STUDY

2.1 SYSTEM DEFINITION

The power systems studied should have the following end performance.

1. Ratings of one, two, five, and ten megawatts.
2. Voltage levels of 5000 to 50,000 volts d-c as follows:
   a. Continuous voltage variation from 5000 to 50,000 volts with constant power output.
   b. Voltage variation in steps, with a constant power output and with 5000 volts as a minimum point and the upper point being 20,000 volts or greater. Limited excitation control will provide variation around these step points.
   c. Voltage variation in steps only with constant power output.
   d. One calculation to show the weight penalty imposed by voltage variation from 5000 to 50,000 volts at constant power by excitation only.
   e. Continuous voltage variation from 5000 to 50,000 volts with the output proportional to the square of the voltage.

The systems studied should conform to the following operating conditions:

1. Generator rotational speeds between 10,000 and 24,000 RPM will be studied. However, if a design point is impractical within this speed range, the speed will be reduced until a design becomes practical.
2. Generator coolant temperatures between 500°F and 1500°F.
3. Generator bearings and seals are not a part of this study.

4. The generator coolant will be an alkali metal. Prime consideration will be given to potassium with alternate coolants being sodium, rubidium, and sodium-potassium eutectic.
5. The generator will be exposed to alkali metal vapors which will be considered to be present when preparing the parametric data.
6. Materials and components used shall be based on the projected improvements of the present materials five years hence.

2.2 SCOPE OF THE STUDY

Parametric data shall be developed and presented in graphic or tabular form, with a technical discussion, on the following:

Generators - Generator data shall be developed over the range of variables for rating, speed and temperature as stated in section 2.1. Frequency shall be determined for minimum and maximum design points and held constant for other designs where practical.

Seals and Bearings - Consideration shall not be given to seals, bearings, insulation and other periphery materials.

Transmission Lines - Materials considered for transmission lines shall be copper, aluminum, and silver.

Generator Excitation and Control - Methods of generator excitation and control shall be studied to meet the required output voltages and rating. Components to be included in the study are silicon-controlled rectifiers, magnetic amplifiers with silicon rectifiers, high-temperature tubes and magnetic amplifiers with gallium arsenide or silicon carbide high-temperature-diodes.

Transformers and Rectifiers - Transformers and rectifiers shall be studied to meet the end performance. The influencing parameters shall be weight, efficiency, operating temperature, insulation system, magnetic materials, coil materials, and frequency.

A maximum of twenty mutually selected design points will be calculated to determine the effects of contemplated advances in techniques which, although not expected to be available in five years with the present level of effort, could be made available with increased effort.

After the parametric data has been prepared, three conceptual designs for the electric power generation and transmission systems will be selected and three system designs will be prepared. The systems selection must take into account the thermal to mechanical energy conversion system (nuclear reactor, turbine, and heat rejection radiator) and the electric propulsion engines or electric power utilization apparatus.

Problem areas which require research to insure successful development of these designs will be summarized and suggested programs included in the final technical report.

No component fabrication and testing shall be required for this program.

3.0 SECOND QUARTER PROGRESS

This report covers the progress and technical data for the second quarter of contract NAS 5-1234, Space Electric Power Systems Study.

The purpose and scope of contract NAS 5-1234 are stated in Sections 1.0 and 2.0 of the technical report.

Summary

The general objective of the study program is to develop parametric data for the generation, control, conversion and transmission of electric power for space vehicles. The coolant temperature for the generator is between 500°F and 1500°F. The ratings to be studied are between one and ten megawatts. Voltage levels for the system are between 5000 and 50,000 volts d-c.

This section presents the technical data developed during the three-month period ending May 8, 1962.

In compliance with the objectives of the study program, the technical information compiled during this period covers the following items:

1. Generator designs for two, five, and ten-megawatts over the voltage, temperature, and speed range.
2. Parametric data of generator weight and efficiency as a function of system rating.
3. Parametric data of weight and efficiency for electrical conversion and control devices as a function of system rating.

3.1 Generator Parametric Data and Analysis

The weight given for each design does not include the weight of rotor-shaft extensions, bearings, end bells, cooling tubes, or terminal boards. The calculated electrical weights are, however, sufficient for the comparisons. For the generator ratings considered, the weight of the above items will add about 20% to the electrical weights.

The length given for each design is the distance between the tips of the stator winding end extensions. The generator end bell lengths are not included because they are small in comparison to the overall generator lengths for the generator ratings considered.

Because the designs consider only incremental wire sizes, variations occur in the generator designs as the wire size and number of conductors per slot are changed to obtain the desired generator parameters. Consequently, the resulting designs may show some small variations in weight and efficiency.

SAE 4340 rotor steel was used for the 500°F, two, five, and ten-megawatt designs. At coolant temperatures of 800°F and above Westinghouse-Nivco rotor steel was used to provide suitable high temperature strength. At a steel temperature of 600°F, rotor-core flux densities in the order of 85 KL/in^2 were possible using the SAE 4340 steel, while at steel temperatures of 900°F and 1200°F rotor-core flux densities were limited to about 60 KL/in^2 and 55 KL/in^2 respectively by the use of Nivco rotor steel. The reduced flux densities at steel temperatures above 600°F required a larger rotor-steel area and increased weight to carry the required flux.

HIPERCO 27 steel was used for the stators in all designs calculated. The HIPERCO 27 curves show little difference in magnetic characteristics at steel temperatures of 600°F and 900°F for flux densities in the order of 120 KL/in^2 to 140 KL/in^2. At a steel temperature of 1200°F the reduction in stator flux densities (about 10%) required an increase in stator-steel weight to carry the required flux.

3.1.1 Two-Megawatt Generator Designs

Summary

The weight and efficiency vs. speed curves indicate the desirability of 15,000 to 20,000 RPM generators operating at an average coolant temperature of 500°F. At coolant temperatures of 800°F and speeds of 15,000 RPM, the two-megawatt designs exceeded the stress limit of the rotor steel.

The weight and efficiency vs. voltage curves in general show small effect on weight of variations over the 500 to 2140 generator voltage range. Voltage variation produced a somewhat more significant effect on efficiency. In general, voltages of 1000 and 1500 volts resulted in designs with the least weight and the highest efficiencies.

The following table is a summary of the two-megawatt generator designs, in order of increasing weight and decreasing efficiency.

DESIGN	ELECTRICAL WEIGHT	DESIGN	% EFF.
1000 V., 15,000 RPM, 500°F	967 lbs.	1000 V., 15,000 RPM, 500°F	95.8%
1500 V., 15,000 RPM, 500°F	988 lbs.	1000 V., 20,000 RPM, 500°F	95.6%
1000 V., 20,000 RPM, 500°F	1009 lbs.	1500 V., 20,000 RPM, 500°F	95.4%
500 V., 15,000 RPM, 500°F	1038 lbs.	1500 V., 15,000 RPM, 500°F	95.3%
1500 V., 20,000 RPM, 500°F	1039 lbs.	500 V., 15,000 RPM, 500°F	95.2%
2140 V., 20,000 RPM, 500°F	1126 lbs.	2140 V., 20,000 RPM, 500°F	95.2%
500 V., 20,000 RPM, 500°F	1207 lbs.	500 V., 20,000 RPM, 500°F	95.2%

Combining like design points from above, the three best overall two-megawatt generator designs are:

1000 V., 15,000 RPM, 500°F	967 lbs.	95.8% Eff.
1500 V., 15,000 RPM, 500°F	988 lbs.	95.3% Eff.
1000 V., 20,000 RPM, 500°F	1009 lbs.	95.6% Eff.

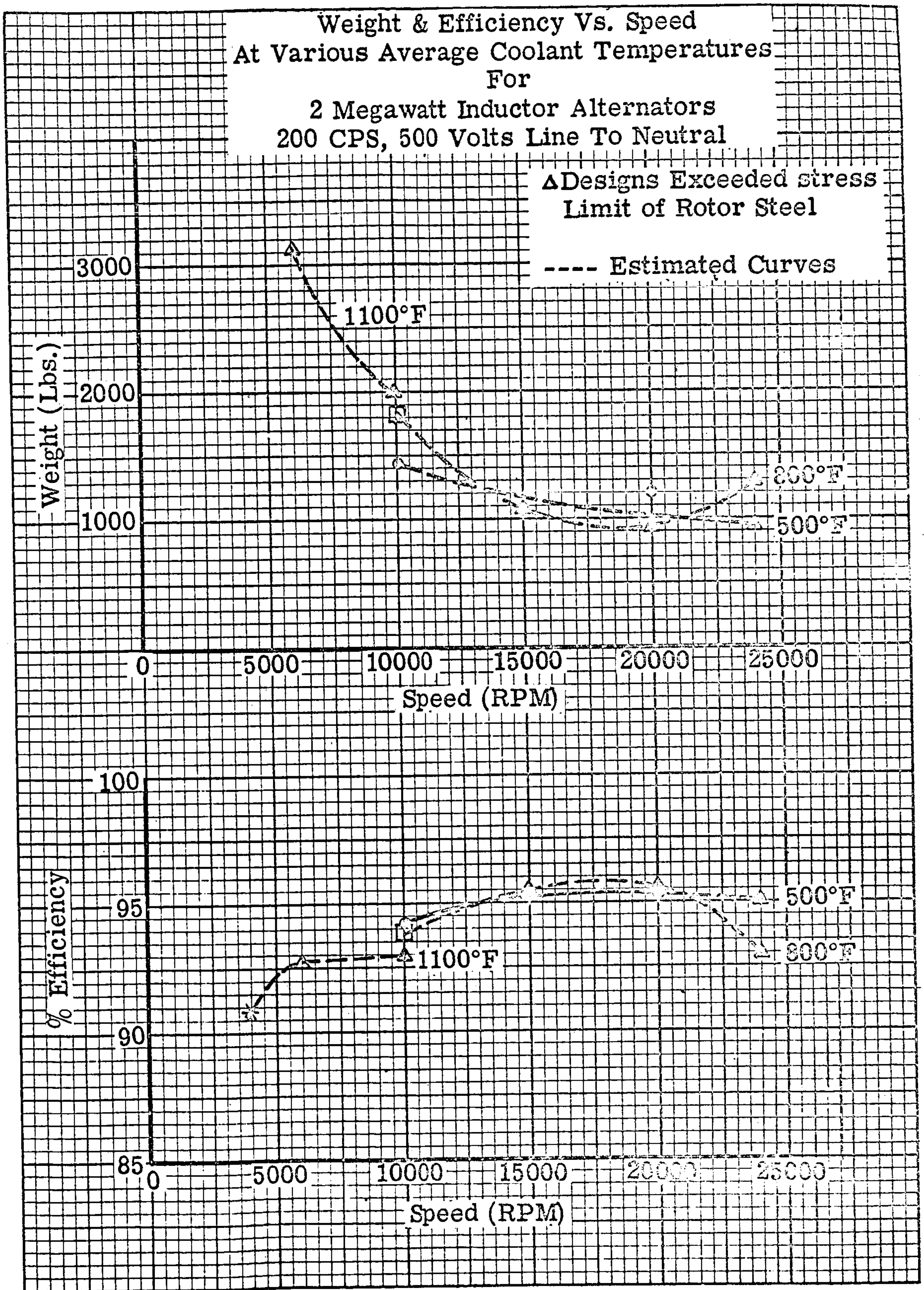
Weight vs. Speed Curves (Figures 3.1.1-1, 2, 3, and 4)

At an average coolant temperature of 500°F, two-megawatt-generator speeds up to 20,000 RPM were possible without exceeding the stress limit of the rotor steel. The lightest weight practical designs were obtained at speeds of 15,000 tp 20,000 RPM. In general, a speed increase results in a decrease in generator weight. In a few cases, however, the calculated 15,000 RPM designs showed a slight (2 - 5%) weight advantage over 20,000 RPM designs, due possibly to better combinations of poles, slots, and conductor sizes in some of the 15,000 RPM designs.

At an average coolant temperature of 800°F, designs at speeds above 10,000 RPM exceeded the stress limit of the rotor steel. At 10,000 RPM, the 500°F designs were found to be in the order of 25% lighter in weight (see designs 78 through 85). The increased weight of the 800°F designs, as explained previously, is partially caused by the need to generate a higher voltage to overcome the increased IR drop.

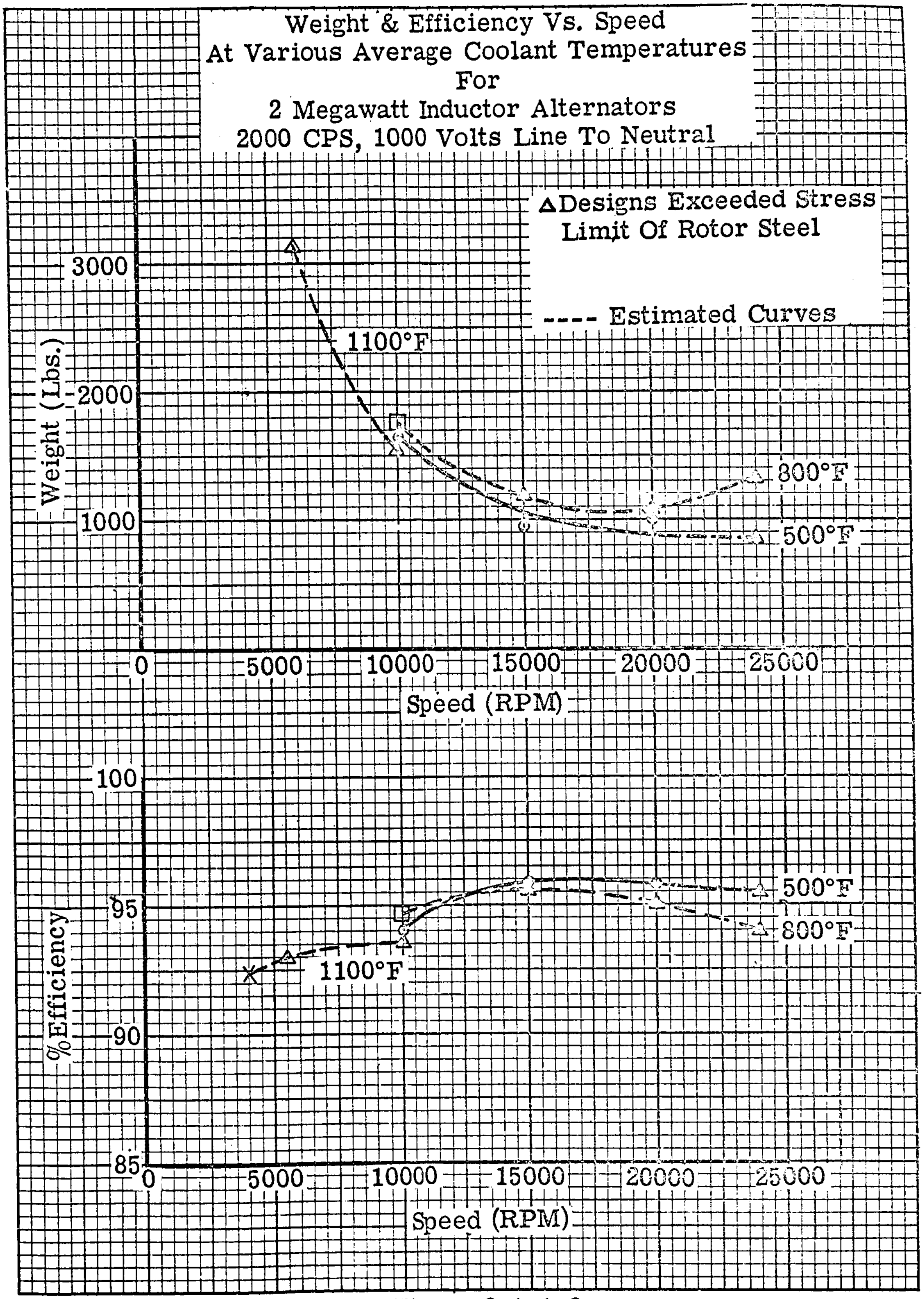
At an average coolant temperature of 1100°F, designs at 6000 RPM exceeded the stress limit of the rotor steel. 4000 RPM, 1100°F designs (122 through 125) did not exceed the rotor-steel stress limit, but the 4000 RPM designs were found to be several times heavier than higher speed designs.

No 1500°F designs were considered for a generator rating of 2-megawatts, because previous 1-megawatt generator designs at 1500°F were not found practical.



Weight & Efficiency Vs. Speed
At Various Average Coolant Temperatures
For
2 Megawatt Inductor Alternators
200 CPS, 500 Volts Line To Neutral
ΔDesigns Exceeded stress Limit of Rotor Steel
---- Estimated Curves
Weight (Lbs.)
3000
2000
1000
1100°F
800°F
500°F
0
5000
10000
15000
20000
25000
Speed (RPM)
% Efficiency
100
95
90
85
500°F
800°F
1100°F
0
5000
10000
15000
20000
25000
Speed (RPM)

Figure 3. 1. 1-1



Weight & Efficiency Vs. Speed
At Various Average Coolant Temperatures
For
2 Megawatt Inductor Alternators
2000 CPS, 1000 Volts Line To Neutral
△Designs Exceeded Stress Limit Of Rotor Steel
---- Estimated Curves
Weight (Lbs.)
3000
2000
1000
0
5000
10000
15000
20000
25000
Speed (RPM)
1100°F
800°F
500°F
%Efficiency
100
95
90
85
0
5000
10000
15000
20000
25000
Speed (RPM)
500°F
800°F
1100°F

Figure 3. 1. 1-2

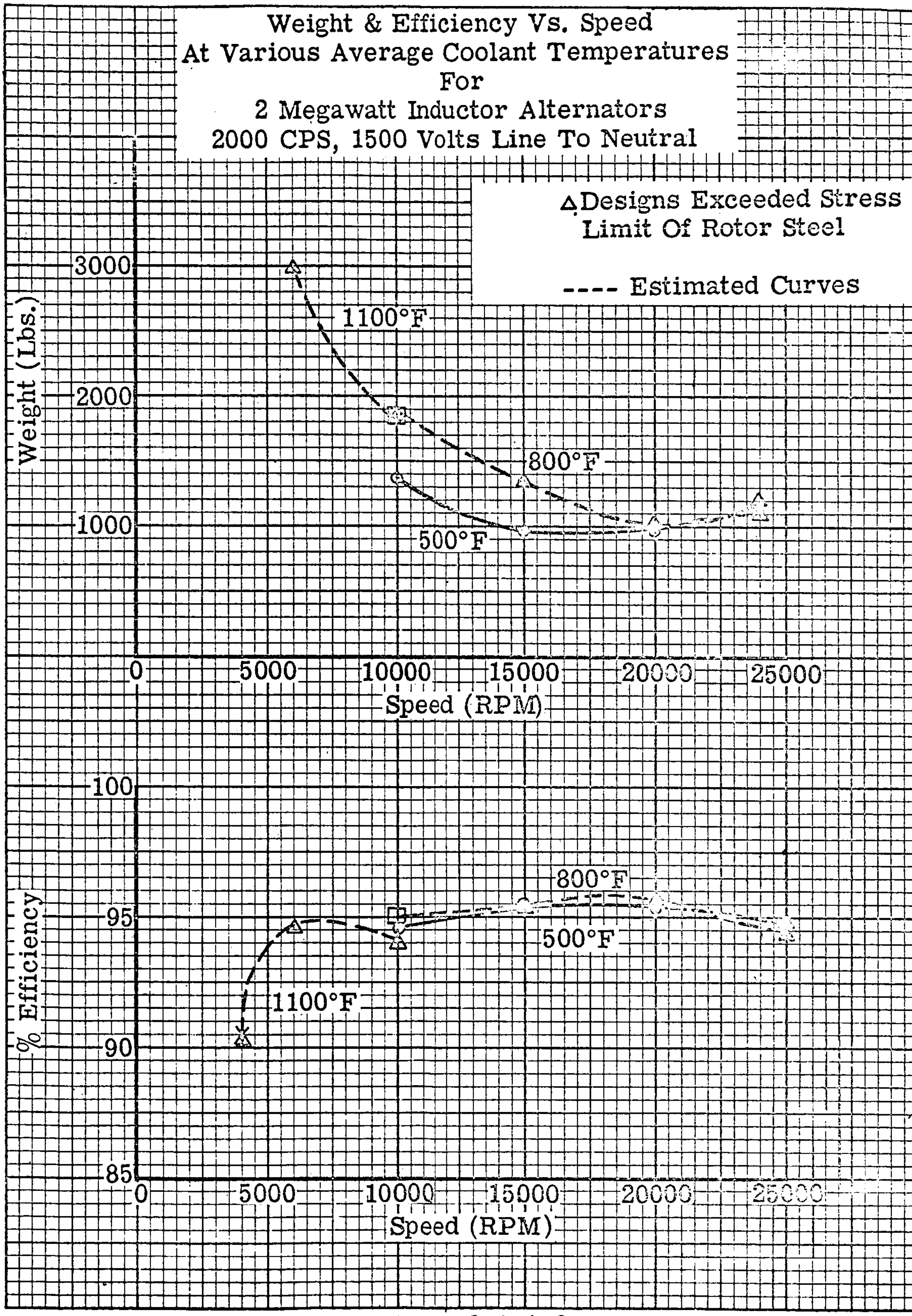

Weight & Efficiency Vs. Speed
At Various Average Coolant Temperatures
For
2 Megawatt Inductor Alternators
2000 CPS, 1500 Volts Line To Neutral
△Designs Exceeded Stress Limit Of Rotor Steel
---- Estimated Curves
Weight (Lbs.)
3000
2000
1000
1100°F
800°F
500°F
0
5000
10000
15000
20000
25000
Speed (RPM)
% Efficiency
100
95
90
85
800°F
500°F
1100°F
0
5000
10000
15000
20000
25000
Speed (RPM)

Figure 3.1.1-3

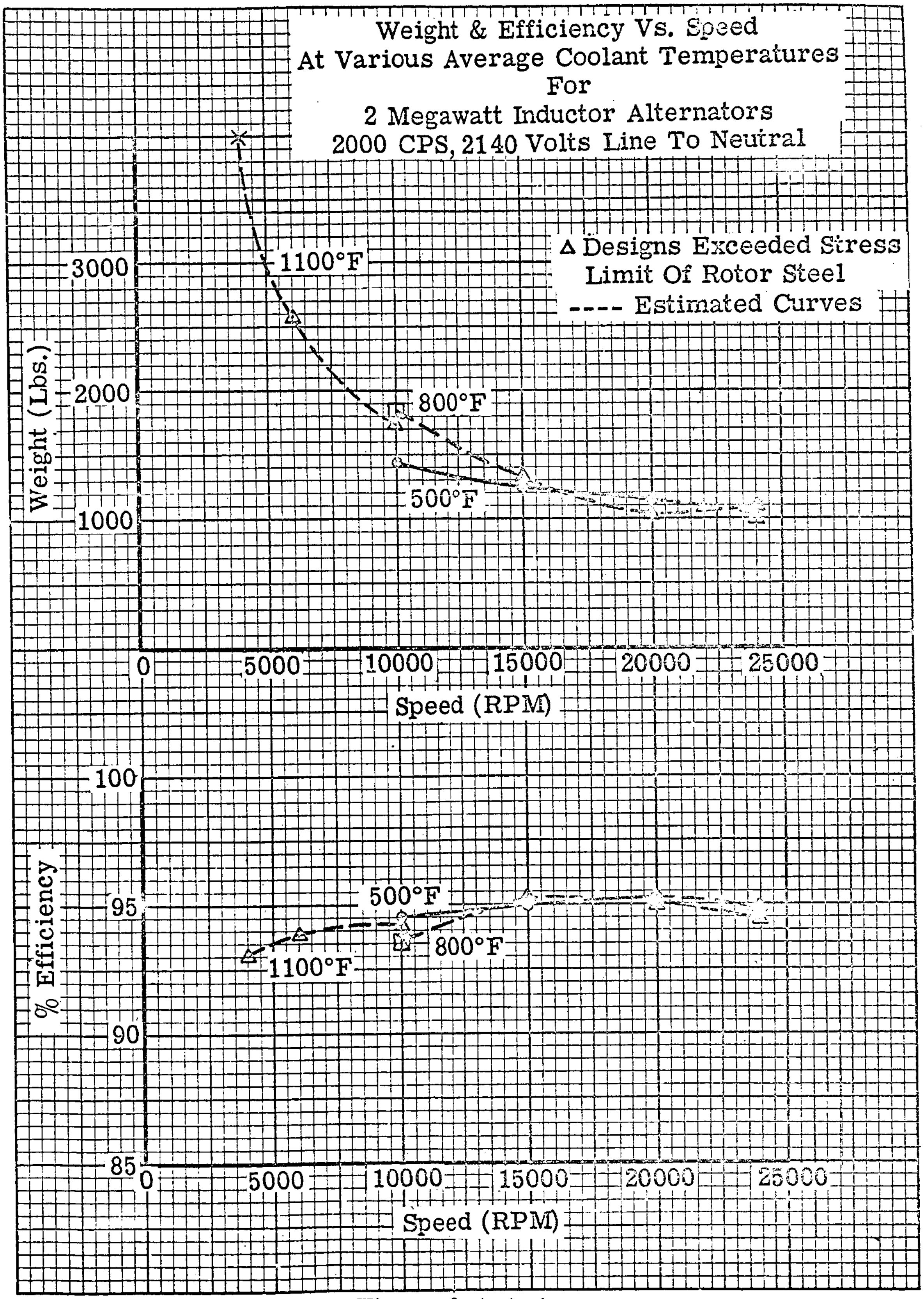

Weight & Efficiency Vs. Speed
At Various Average Coolant Temperatures
For
2 Megawatt Inductor Alternators
2000 CPS, 2140 Volts Line To Neutral
Δ Designs Exceeded Stress Limit Of Rotor Steel
---- Estimated Curves
Weight (Lbs.)
3000
2000
1000
1100°F
800°F
500°F
0
5000
10000
15000
20000
25000
Speed (RPM)
% Efficiency
100
95
90
85
500°F
800°F
1100°F
0
5000
10000
15000
20000
25000
Speed (RPM)

Figure 3. 1. 1-4

Based upon the curves of Weight vs. Speed for two-megawatt generators, the 500°F designs for speeds from 15,000 to 20,000 RPM have the least weight. Two-megawatt, 800°F designs must be limited to speeds of 10,000 RPM or less and two-megawatt 1100°F designs must be limited to speeds of 4000 RPM or less so that rotor-steel stress limits are not exceeded.

Efficiency vs. Speed Curves (Figures 3.1.1-1, 2, 3, and 4)

The two-megawatt designs showed a general increase in efficiency as rated speed was increased up to 20,000 RPM. This was true for the 500°F designs because the copper losses decreased faster than the iron losses increased, and for the 800°F designs because the copper losses decreased faster than the windage losses increased. From 20,000 to 24,000 RPM the 500°F designs showed a slight decrease in efficiency, due principally to larger increases in iron losses. The windage loss at 500°F was negligible compared to the other losses. From 20,000 tp 24,000 RPM the 800°F designs showed a larger decrease in efficiency than the 500°F designs, because the windage losses about doubled in going from 20,000 RPM to 24,000 RPM.

Based upon the 2-megawatt generator Efficiency vs. Speed Curves, speeds of 15,000 and 20,000 RPM resulted in the highest efficiencies. The efficiencies at both these speeds were about equal for the practical 500°F designs.

Weight vs. Voltage Curves (Figure 3.1.1-5 through 3.1.1-10)

The Weight vs. Voltage curves at various speeds (figures 3.1.1-5, 6, and 7) show that for the 15,000 RPM and 20,000 RPM speeds, the lowest weights occurred at generator voltages of 1000 and 15000 volts. At 10,000 RPM, 500°F,

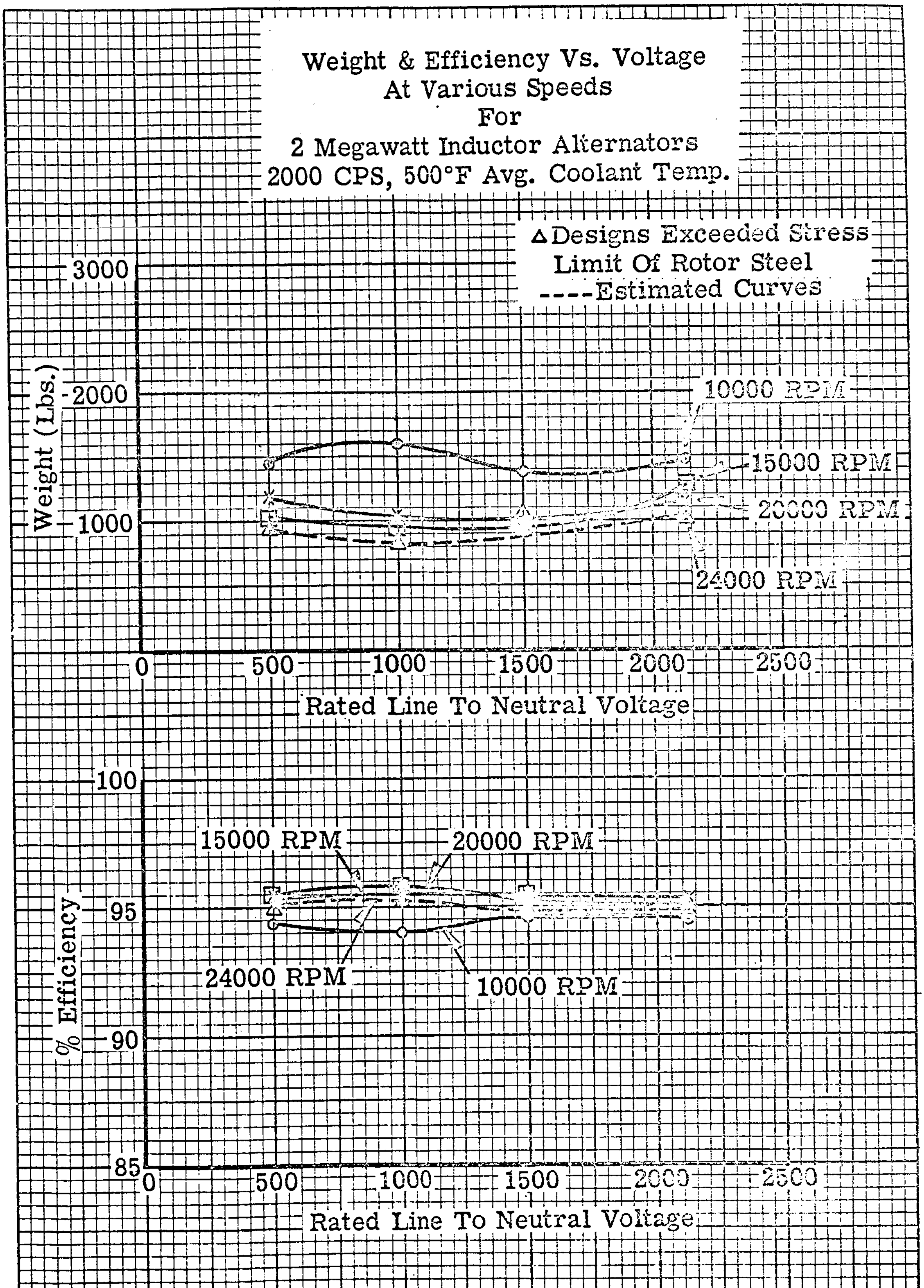

Weight & Efficiency Vs. Voltage
At Various Speeds
For
2 Megawatt Inductor Alternators
2000 CPS, 500°F Avg. Coolant Temp.
Δ Designs Exceeded Stress Limit Of Rotor Steel
----Estimated Curves
Weight (Lbs.)
3000
2000
1000
10000 RPM
15000 RPM
20000 RPM
24000 RPM
0
500
1000
1500
2000
2500
Rated Line To Neutral Voltage
% Efficiency
100
95
90
85
15000 RPM
20000 RPM
24000 RPM
10000 RPM
0
500
1000
1500
2000
2500
Rated Line To Neutral Voltage

Figure 3.1.1-5

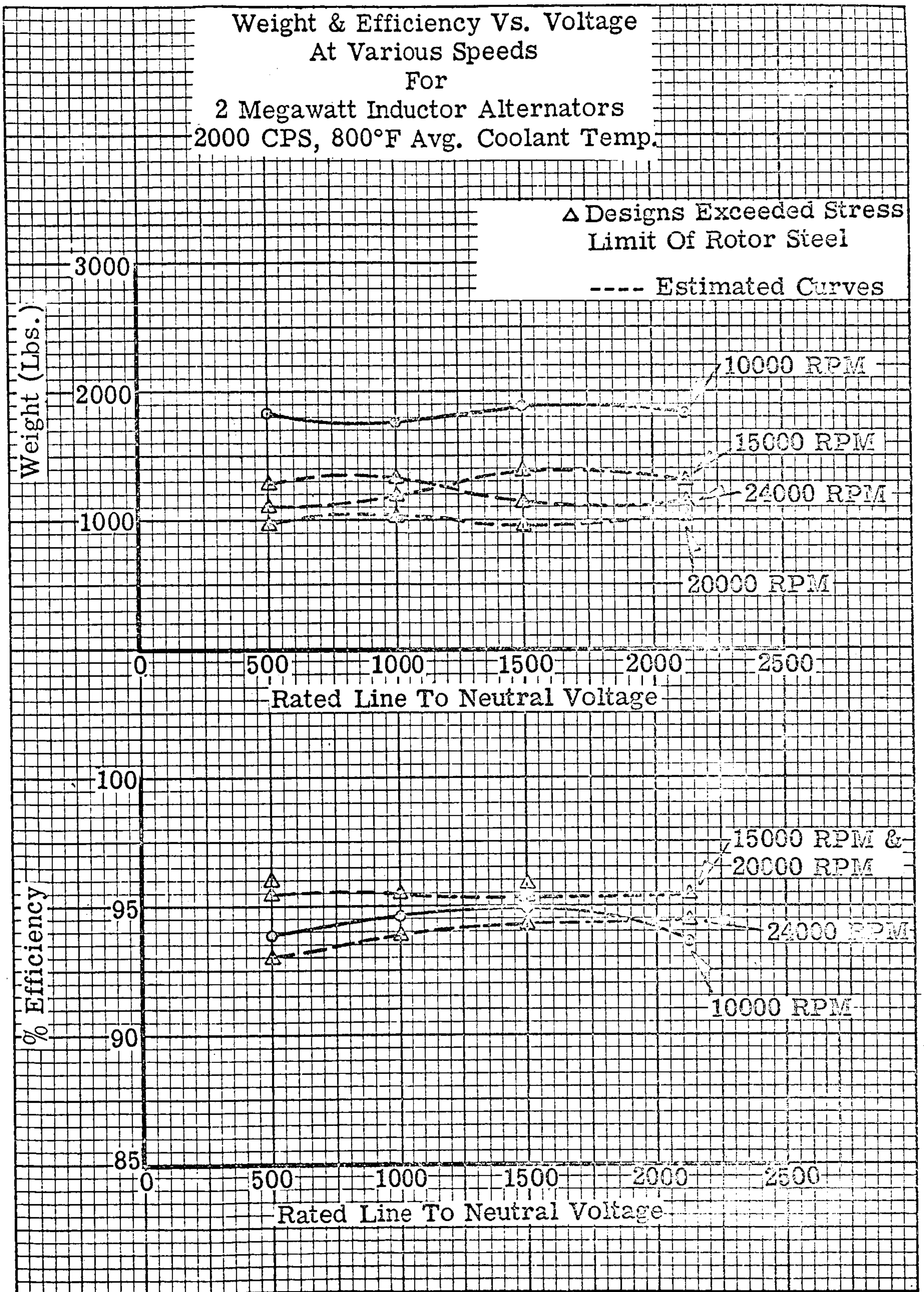

Weight & Efficiency Vs. Voltage
At Various Speeds
For
2 Megawatt Inductor Alternators
2000 CPS, 800°F Avg. Coolant Temp.
Δ Designs Exceeded Stress Limit Of Rotor Steel
---- Estimated Curves
Weight (Lbs.)
3000
2000
1000
10000 RPM
15000 RPM
24000 RPM
20000 RPM
0
500
1000
1500
2000
2500
Rated Line To Neutral Voltage
% Efficiency
100
95
90
85
15000 RPM &
20000 RPM
24000 RPM
10000 RPM
0
500
1000
1500
2000
2500
Rated Line To Neutral Voltage

Figure 3. 1. 1-6

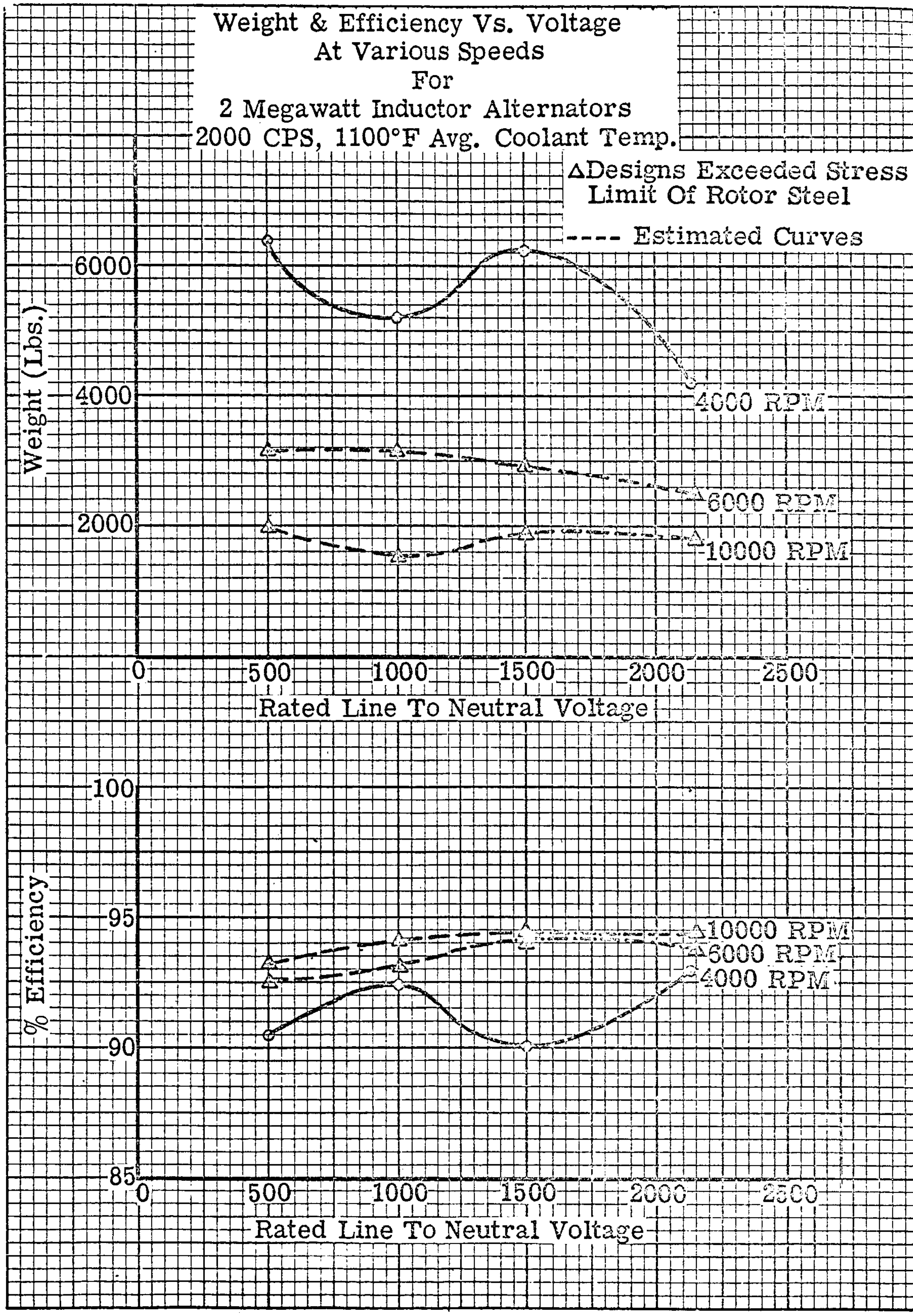

Weight & Efficiency Vs. Voltage
At Various Speeds
For
2 Megawatt Inductor Alternators
2000 CPS, 1100°F Avg. Coolant Temp.
ΔDesigns Exceeded Stress Limit Of Rotor Steel
---- Estimated Curves
Weight (Lbs.)
6000
4000
2000
0
500
1000
1500
2000
2500
4000 RPM
6000 RPM
10000 RPM
Rated Line To Neutral Voltage
% Efficiency
100
95
90
85
10000 RPM
6000 RPM
4000 RPM
0
500
1000
1500
2000
2500
Rated Line To Neutral Voltage

Figure 3. 1. 1-7

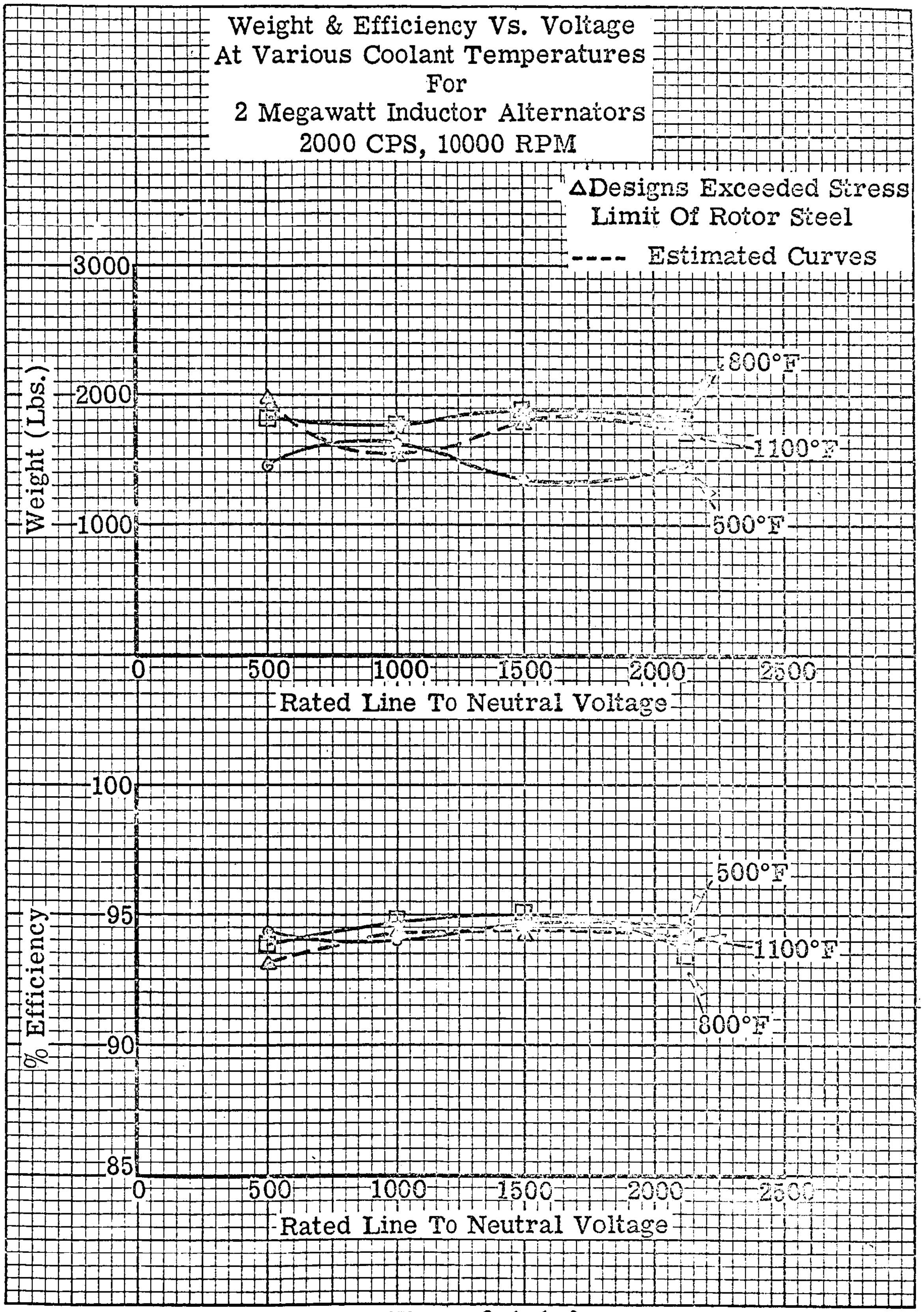

Weight & Efficiency Vs. Voltage
At Various Coolant Temperatures
For
2 Megawatt Inductor Alternators
2000 CPS, 10000 RPM
△Designs Exceeded Stress Limit Of Rotor Steel
---- Estimated Curves
Weight (Lbs.)
3000
2000
1000
800°F
1100°F
500°F
0
500
1000
1500
2000
2500
Rated Line To Neutral Voltage
% Efficiency
100
95
90
85
500°F
1100°F
800°F
0
500
1000
1500
2000
2500
Rated Line To Neutral Voltage

Figure 3.1.1-8

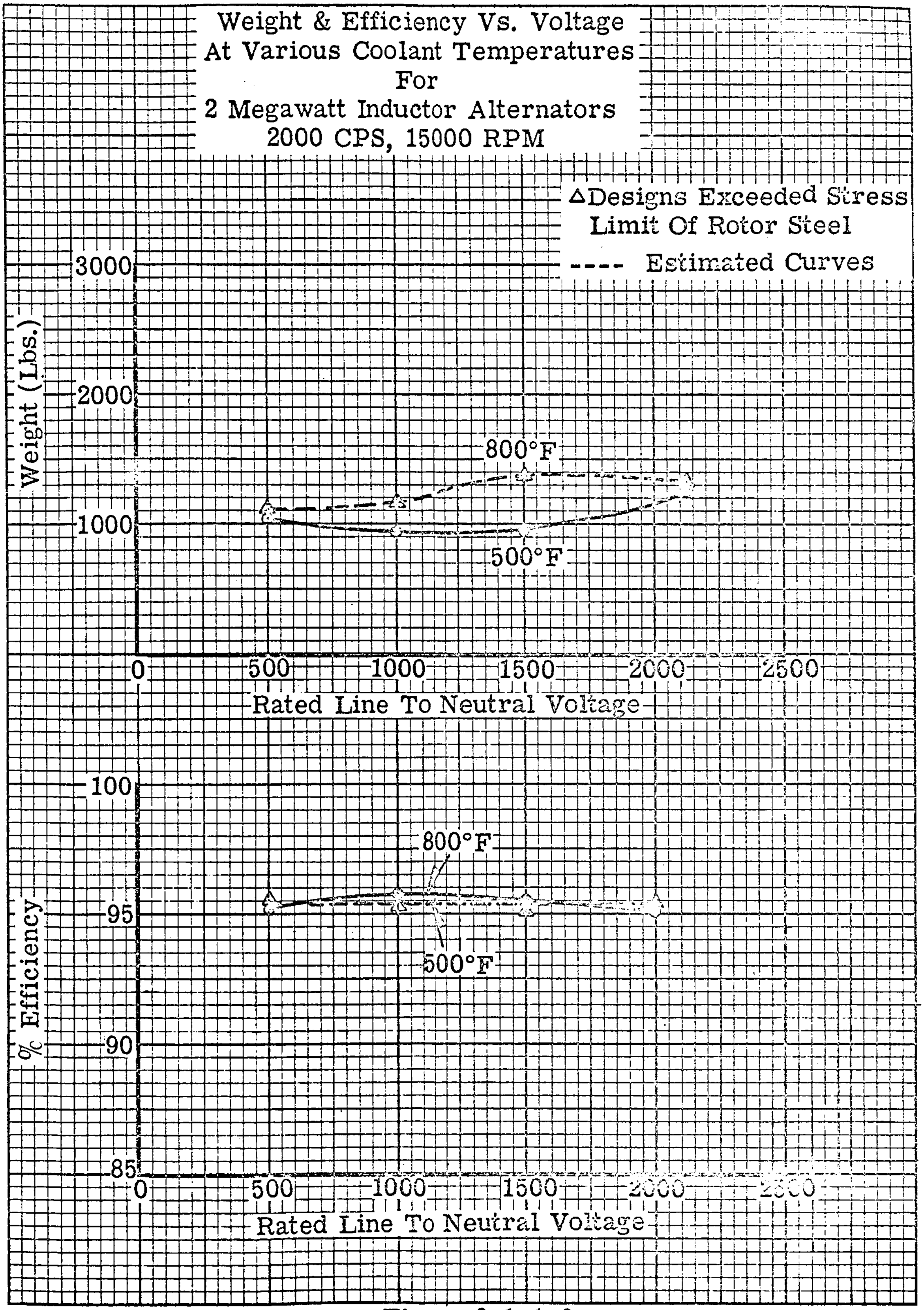

Weight & Efficiency Vs. Voltage
At Various Coolant Temperatures
For
2 Megawatt Inductor Alternators
2000 CPS, 15000 RPM
△Designs Exceeded Stress Limit Of Rotor Steel
---- Estimated Curves
Weight (Lbs.)
3000
2000
1000
800°F
500°F
0
500
1000
1500
2000
2500
Rated Line To Neutral Voltage
% Efficiency
100
95
90
85
800°F
500°F
0
500
1000
1500
2000
2500
Rated Line To Neutral Voltage

Figure 3.1.1-9

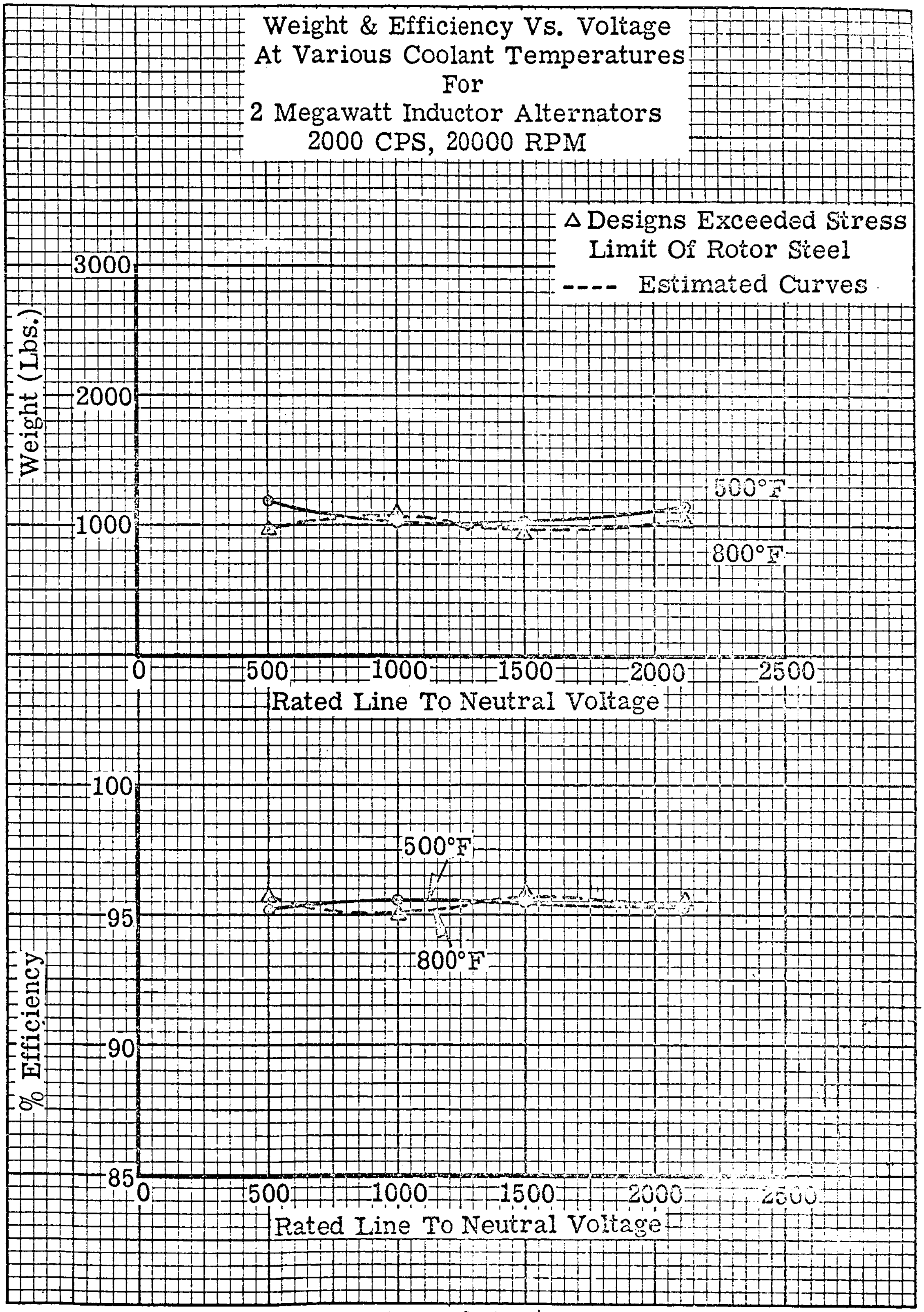


Figure 3. 1. 1-10

a voltage of 1500 volts produced the lightest weight design. A 10,000 RPM, 800°F, a voltage of 1000 volts produced the lightest weight design. The 1100°F, 4000 RPM, curve shows rather extreme variations in weight at different voltage levels. The cause of this variation might be the effect of varying slot configuration and conductor sizes in the low speed designs, resulting in larger rotor diameters and longer stack lengths in the 500 V and 1500 V designs.

The Weight vs. Voltage curves at various temperatures (figures 3.1.1-8, 9, and 10) illustrate the weight advantage of the practical, lower-temperature designs, and again show the 500°F, 15,000 and 20,000 RPM designs at voltages of 1500 and 2000 volts to be the best designs from a weight standpoint.

Based upon the Weight vs. Voltage Curves, a two-megawatt generator voltage range of 1000 to 1500 volts appears to result in the lightest weight designs.

Efficiency vs. Voltage Curves (Figures 3.1.1-5 through 3.1.1-10)

As would be expected, the 2140 V designs had, in general, the highest core losses and lowest copper losses. As the rated voltage was decreased to 500 volts, the required increase in rated current, in most cases, caused an increase in the copper (I^2R) losses and a decrease in the core losses. As shown in figures 3.1.1-5, 6, and 7, the lowest combined losses and thus the highest efficiencies occurred in the 1000 to 1500 voltage range for the practical designs at 500°F and 800°F.

The 1100°F, 4000 RPM curve (figure 3.1.1-7) shows relatively lower efficiencies at 500 V and at 1500 V than at 1000 V and 2140 V designs, because the combination of parameters used for the 500 V and 1500 V designs resulted in larger rotor diameters and higher iron and windage losses.

Figures 3.1.1-8, 9, and 10, for various coolant temperatures, show that 1000 and 1500 volt designs have an efficiency advantage at 500°F and 800°F. The 800°F, 10,000 RPM designs at 1000 and 1500 volts show a slightly higher efficiency than the 500°F, 10,000 RPM designs, due to combinations of design parameters which produced relatively low iron losses for the 800°F, 10,000 RPM, 1000 and 1500 volt designs.

Based upon the Efficiency vs. Voltage curves, a two-megawatt generator voltage range of 1000 to 1500 volts appears to produce the highest efficiency designs.

TABLE 3.1.1-1

2 Megawatt Generator Designs - 2000 cps

DE-SIGN NO.	AVG. COOL-ANT TEMP. (°F)	GEN. VOLTS L-N	% EFFI-CIENCY	GEN. WT. (LBS.)	FLD. PWR. (KW)	LOSSES (KW) Fe = Iron Cu = Copper W = Windage			SINGLE STK. LGTH (IN)	ROTOR O.D. (IN)	MAX. GEN. O.D. (IN)	TOTAL GEN. LGTH (IN)	APPROX. AVG. AC & FLD. WDG. TEMP. RISE (°F)	P.U. X_d	MAX. ALLOW-ABLE ROTOR STRESS (psi)	ACT-UAL MAX. ROTOR STRESS (psi)
						Fe	Cu	W								
						10000 RPM										
78	500	2140	94.5	1446	11.6	65.5	51.2	.024	8.73	16.4	25.9	21.1	154	1.34	63700	16841
79	500	1500	94.7	1374	11.9	59.0	53.7	.022	8.78	16.0	25.1	21.2	154	1.48	63700	16143
80	500	1000	94.0	1624	4.70	68.8	59.3	.037	8.69	18.0	27.1	19.2	162	1.39	63700	20079
81	500	500	94.4	1424	7.28	63.4	55.8	.029	8.81	17.1	25.8	21.4	162	1.38	63700	18255
82	800	2140	93.6	1825	5.92	89.1	44.4	2.29	7.46	21.0	30.0	18.9	177	1.10	30000	27185
83	800	1500	95.0	1872	5.45	62.5	40.0	1.96	8.12	20.3	29.2	20.0	144	1.10	30000	25628
84	800	1000	94.6	1774	5.87	55.9	55.4	1.80	8.15	20.0	28.5	20.1	149	1.36	30000	24675
85	800	500	93.8	1829	5.77	78.1	52.0	2.11	8.16	20.6	29.2	20.4	177	1.26	30000	26262
86	1100	2140	94.4	1741	16.3	40.2	64.7	14.0	7.79	19.7	28.8	19.2	172	1.28	11200	24160*
87	1100	1500	94.4	1849	20.6	48.6	65.9	14.4	8.56	19.9	28.5	20.8	142	1.21	11200	24447*
88	1100	1000	94.2	1569	16.0	34.3	77.1	12.4	7.43	19.2	27.9	18.6	172	1.35	11200	22934*
89	1100	500	93.1	1991	7.35	64.0	64.9	19.8	8.30	21.2	29.9	20.6	192	1.32	11200	27771*
90	1500	2140	74.7	10312	18.4	36.5	95.2	546	22.9	29.3	40.9	49.2	242	1.40	750	53107*
91	1500	1500	66.8	13159	29.3	50.3	82.4	861	23.5	32.2	44.8	50.4	242	.80	750	64009*
92	1500	1000	74.1	10991	21.4	37.0	101	562	24.2	29.4	41.0	52.0	252	1.30	750	54014*
93	1500	500	78.8	7715	118	30.9	209	297	21.3	25.7	36.9	46.1	224	1.79	750	41164*

*Designs exceeded stress limit of rotor steel

TABLE 3.1.1-2

2 Megawatt Generator Designs - 2000 cps

DESIGN NO.	AVG. COOLANT TEMP. (°F)	GEN. VOLTS L-N	% EFFICIENCY	GEN. WT. (LBS.)	FLD. PWR. (KW)	LOSSES (KW) Fe = Iron Cu = Copper W = Windage: Fe	Cu	W	SINGLE STK. LGTH (IN)	ROTOR O.D. (IN)	MAX. GEN. O.D. (IN)	TOTAL GEN. LGTH (IN)	APPROX. AVG. AC & FLD. WDG. TEMP. RISE (°F)	P.U. X_d	MAX. ALLOWABLE ROTOR STRESS (psi)	ACTUAL MAX. ROTOR STRESS (psi)
						15000 RPM										
94	500	2140	95.0	1260	5.57	74.7	30.0	.059	8.34	15.5	24.7	20.6	108	1.43	63700	34103
95	500	1500	95.3	988	8.79	58.6	40.4	.045	6.95	14.6	23.4	18.0	172	1.45	63700	30531
96	500	1000	95.8	967	6.37	56.2	32.5	.051	6.57	15.1	23.7	17.2	152	1.39	63700	32374
97	500	500	95.2	1038	7.37	55.8	45.6	.053	7.45	15.2	23.6	19.0	162	1.51	63700	32732
98	800	2140	95.3	1313	6.77	62.4	32.3	3.69	6.67	18.2	26.8	17.4	150	1.10	30000	46317*
99	800	1500	95.3	1380	7.11	61.2	34.3	3.80	7.25	18.3	26.7	18.6	150	1.05	30000	46895*
100	800	1000	95.5	1184	6.30	54.2	36.3	3.33	6.22	17.8	26.0	16.7	169	1.15	30000	44387*
101	800	500	95.4	1092	6.54	52.9	40.2	3.01	5.91	17.4	25.4	26.2	177	1.32	30000	42580*
						20000 RPM										
102	500	2140	95.2	1126	5.83	77.6	23.9	.125	7.96	15.3	23.9	20.0	159	1.11	63700	59000
103	500	1500	95.4	1039	5.84	70.7	25.9	.114	7.50	15.0	23.5	19.3	147	1.19	63700	56858
104	500	1000	95.6	1009	5.72	67.8	24.6	.112	7.41	14.9	23.2	19.2	152	1.16	63700	56520
105	500	500	95.2	1207	5.06	81.8	20.1	.139	8.55	15.6	23.9	21.7	127	.97	63700	61719
106	800	2140	95.2	1063	7.50	63.1	31.3	5.87	6.01	16.8	25.0	16.4	202	1.21	30000	71162*
107	800	1500	95.6	998	6.85	58.3	29.3	5.42	5.83	16.6	24.4	16.2	187	1.33	30000	68916*
108	800	1000	95.1	1088	5.56	68.0	27.7	6.63	5.87	17.3	25.3	16.4	196	1.04	30000	74811*
109	800	500	95.6	988	5.96	56.6	30.6	5.73	5.64	16.8	24.5	14.6	196	1.30	30000	70491*

*Designs exceeded stress limit of rotor steel

TABLE 3.1.1-3

2 Megawatt Generator Designs - 2000 cps

DESIGN NO.	AVG. COOLANT TEMP. (°F)	GEN. VOLTS L-N	% EFFICIENCY	GEN. WT. (LBS.)	FLD. PWR. (KW)	LOSSES (KW) Fe = Iron, Cu = Copper, W = Windage: Fe	Cu	W	SINGLE STK. LGTH (IN)	ROTOR O.D. (IN)	MAX. GEN. O.D. (IN)	TOTAL GEN. LGTH (IN)	APPROX. AVG. AC & FLD. WDG. TEMP. RISE (°F)	P.U. X_d	MAX. ALLOWABLE ROTOR STRESS (psi)	ACTUAL MAX. ROTOR STRESS (psi)
24000 RPM																
110	500	2140	94.9	1045	5.67	86.9	21.3	.190	7.44	14.9	23.5	19.2	170	1.03	63700	81671*
111	500	1500	94.9	1115	5.49	88.9	18.6	.202	8.01	15.2	23.5	20.6	144	1.00	63700	83817*
112	500	1000	95.5	822	5.07	70.5	24.0	.146	6.13	14.1	22.2	17.0	179	1.29	63700	73737*
113	500	500	95.0	966	4.51	86.9	18.4	.187	6.96	14.9	23.2	18.8	162	1.06	63700	81458*
114	800	2140	94.5	1104	4.83	79.7	26.3	10.8	5.82	17.2	25.3	16.4	242	1.33	30000	106536*
115	800	1500	94.4	1127	4.50	80.3	26.2	11.2	5.93	17.3	25.4	16.7	252	1.23	30000	107973*
116	800	1000	94.0	1327	4.26	91.5	22.3	13.7	6.64	18.1	26.3	18.2	212	.96	30000	117449*
117	800	500	93.0	1277	4.22	113.5	24.3	13.0	6.75	17.9	26.0	19.0	242	1.05	30000	114812*
6000 RPM																
118	1100	2140	93.9	2557	13.6	67.4	54.4	8.91	6.05	24.4	35.9	17.2	176	1.11	11200	13253*
119	1100	1500	94.6	2990	8.30	50.9	54.4	9.90	8.35	25.0	35.2	20.1	120	.89	11200	13904*
120	1100	1000	93.1	3175	10.7	42.8	97.0	7.69	10.8	23.7	32.9	25.0	110	1.39	11200	12499*
121	1100	500	92.9	3147	10.5	45.9	100.4	7.66	10.9	23.7	32.7	25.3	142	1.46	11200	12421*
4000 RPM																
122	1100	2140	93.0	4202	14.8	56.7	88.3	4.78	10.0	27.4	38.1	23.2	122	1.35	11200	7464
123	1100	1500	90.2	6247	15.9	89.8	120.6	7.33	14.0	30.0	40.4	31.1	164	1.19	11200	8821
124	1100	1000	92.4	5160	12.1	45.2	115.7	4.66	13.9	27.2	36.9	30.9	122	1.17	11200	7345
125	1100	500	90.6	6419	15.5	83.1	117.7	7.03	14.8	29.7	39.9	32.7	147	1.17	11200	8685

*Designs exceeded stress limit of rotor steel

3.1.2 Five-Megawatt Generator Designs

Summary

The weight and efficiency vs. speed curves indicate the desirability of 10,000 RPM to 15,000 RPM generators operating at an average coolant temperature of 500°F. The number of practical designs at 15,000 RPM, 500°F were limited because some designs exceeded the stress limit of the rotor steel.

At coolant temperatures of 800°F, speeds of 10,000 RPM, the five-megawatt designs exceeded the stress limit of the rotor steel. To maintain reasonable rotor stresses, the maximum speed was 6000 RPM for 800°F designs and 2000 RPM for a limited number of 1100°F designs. The five-megawatt, 800°F and 1100°F designs were several times heavier than the 500°F designs.

The weight and efficiency vs. voltage curves show that for the practical 10,000 RPM, 500°F designs, voltage variation of 500 to 2140 volts had little effect on weight or efficiency. The lowest weight occurs at 1000 volts. A slight efficiency advantage is shown for voltages above 500 volts. Voltages of 500 and 1500 volts produced practical 15,000 RPM designs, while the 1000 and 2140 volt, 15,000 RPM designs, exceeded the stress limit of the rotor steel. The 1500 volt, 15,000 RPM, 500°F design was the lightest five-megawatt design.

The following table is a summary of the best five-megawatt generator designs in order of increasing weight and decreasing efficiency.

DESIGN	ELECTRICAL WEIGHT	DESIGN	% EFF.
1500 V, 15,000 RPM, 500°F	2938 lbs.	2140 V, 10,000 RPM, 500°F	95.8
500 V, 15,000 RPM, 500°F	3132 lbs.	1000 V, 10,000 RPM, 500°F	95.8
1000 V, 10,000 RPM, 500°F	3338 lbs.	1500 V, 15,000 RPM, 500°F	95.7
500 V, 10,000 RPM, 500°F	3392 lbs.	500 V, 10,000 RPM, 500°F	95.3
2140 V, 10,000 RPM, 500°F	3539 lbs.	500 V, 15,000 RPM, 500°F	95.2

Combining like design points from above, the four best five-megawatt generator designs are:

1500 V, 15,000 RPM, 500°F	2938 lbs.	95.7% Eff.
500 V, 15,000 RPM, 500°F	3132 lbs.	95.2% Eff.
1000 V, 10,000 RPM, 500°F	3338 lbs.	95.8% Eff.
500V, 10,000 RPM, 500°F	3392 lbs.	95.3% Eff.

Weight vs. Speed Curves (Figures 3.1.2-1, 2, 3, and 4)

At an average coolant temperature of 500°F, five-megawatt generator speeds up to 10,000 RPM were possible and two designs at 15,000 RPM were possible without exceeding the rotor-steel stress limit. The lightest weight were the two practical 15,000 RPM, 500°F designs (No. 135 and No. 137). The lower voltage 10,000 RPM, 500°F designs were, however, only about 10% heavier than the 15,000 RPM designs. Design No. 127 utilized a combination of parameters in the computer design calculation resulting in a low X_d and a high weight for the design calculated. Further analysis of this design point, and adjustment of computer input data could result in a reduction of weight with a corresponding increase in X_d. This was not done since the data obtained was used for a general choice of operating parameters rather than for the choice of a specific final design.

At an average coolant temperature of 800°F, it was necessary to reduce the speed to 6000 RPM to obtain five-megawatt designs which did not exceed the

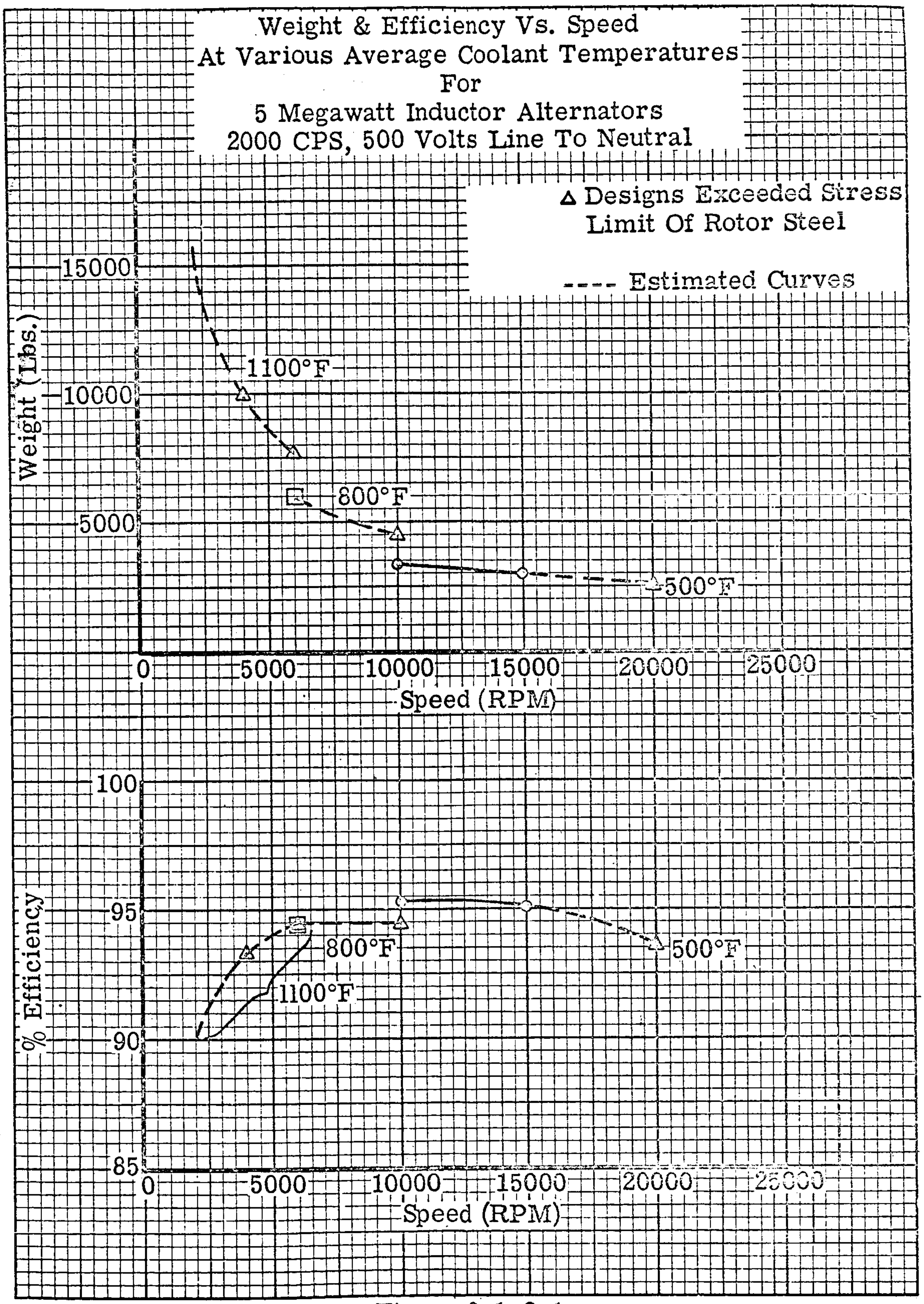

Weight & Efficiency Vs. Speed
At Various Average Coolant Temperatures
For
5 Megawatt Inductor Alternators
2000 CPS, 500 Volts Line To Neutral
Δ Designs Exceeded Stress Limit Of Rotor Steel
---- Estimated Curves
Weight (Lbs.)
15000
10000
5000
1100°F
800°F
500°F
0
5000
10000
15000
20000
25000
Speed (RPM)
% Efficiency
100
95
90
85
800°F
1100°F
500°F
0
5000
10000
15000
20000
25000
Speed (RPM)

Figure 3. 1. 2-1

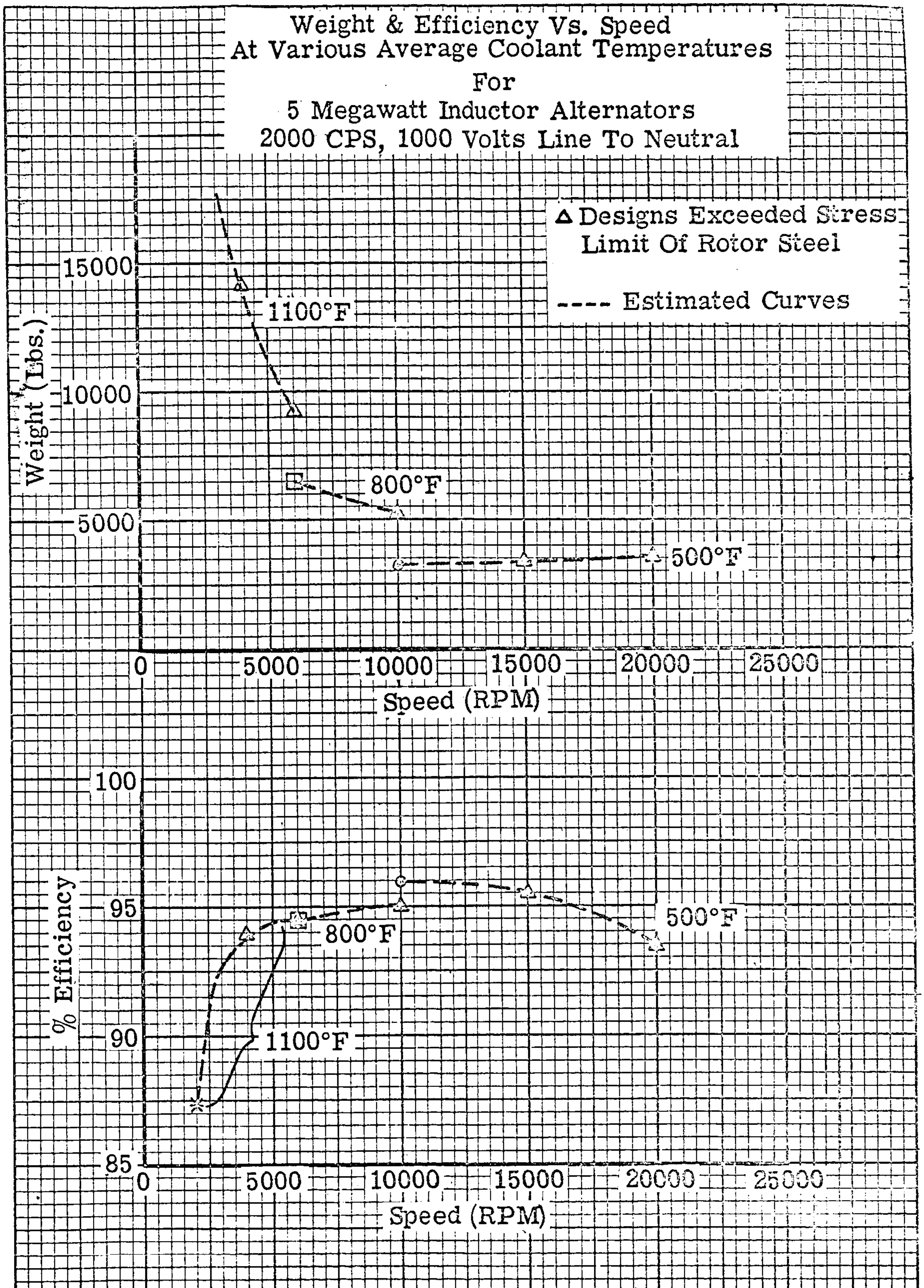

Weight & Efficiency Vs. Speed
At Various Average Coolant Temperatures
For
5 Megawatt Inductor Alternators
2000 CPS, 1000 Volts Line To Neutral
Δ Designs Exceeded Stress Limit Of Rotor Steel
---- Estimated Curves
Weight (Lbs.)
15000
10000
5000
1100°F
800°F
500°F
0
5000
10000
15000
20000
25000
Speed (RPM)
% Efficiency
100
95
90
85
800°F
1100°F
500°F
0
5000
10000
15000
20000
25000
Speed (RPM)

Figure 3. 1. 2-2

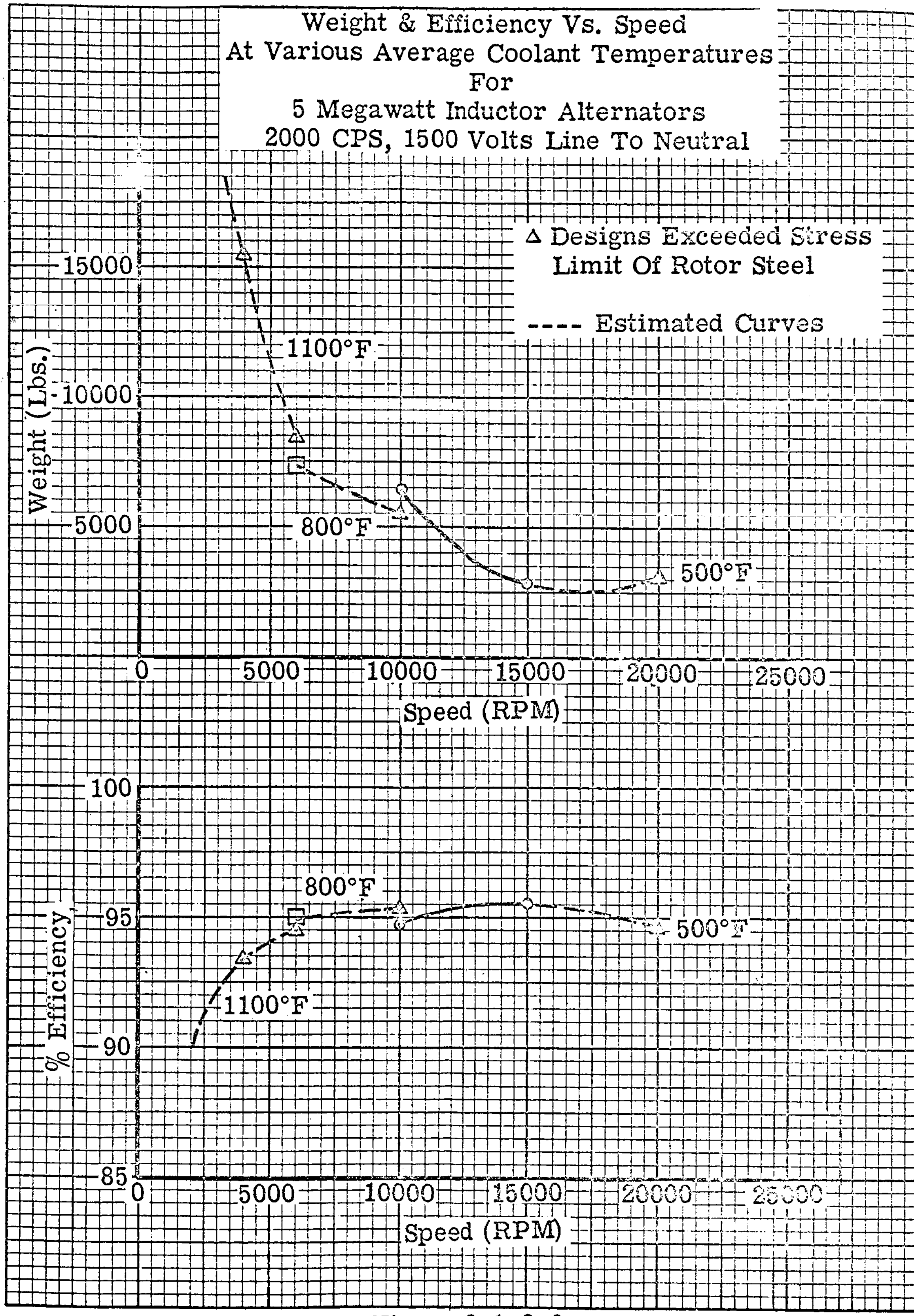
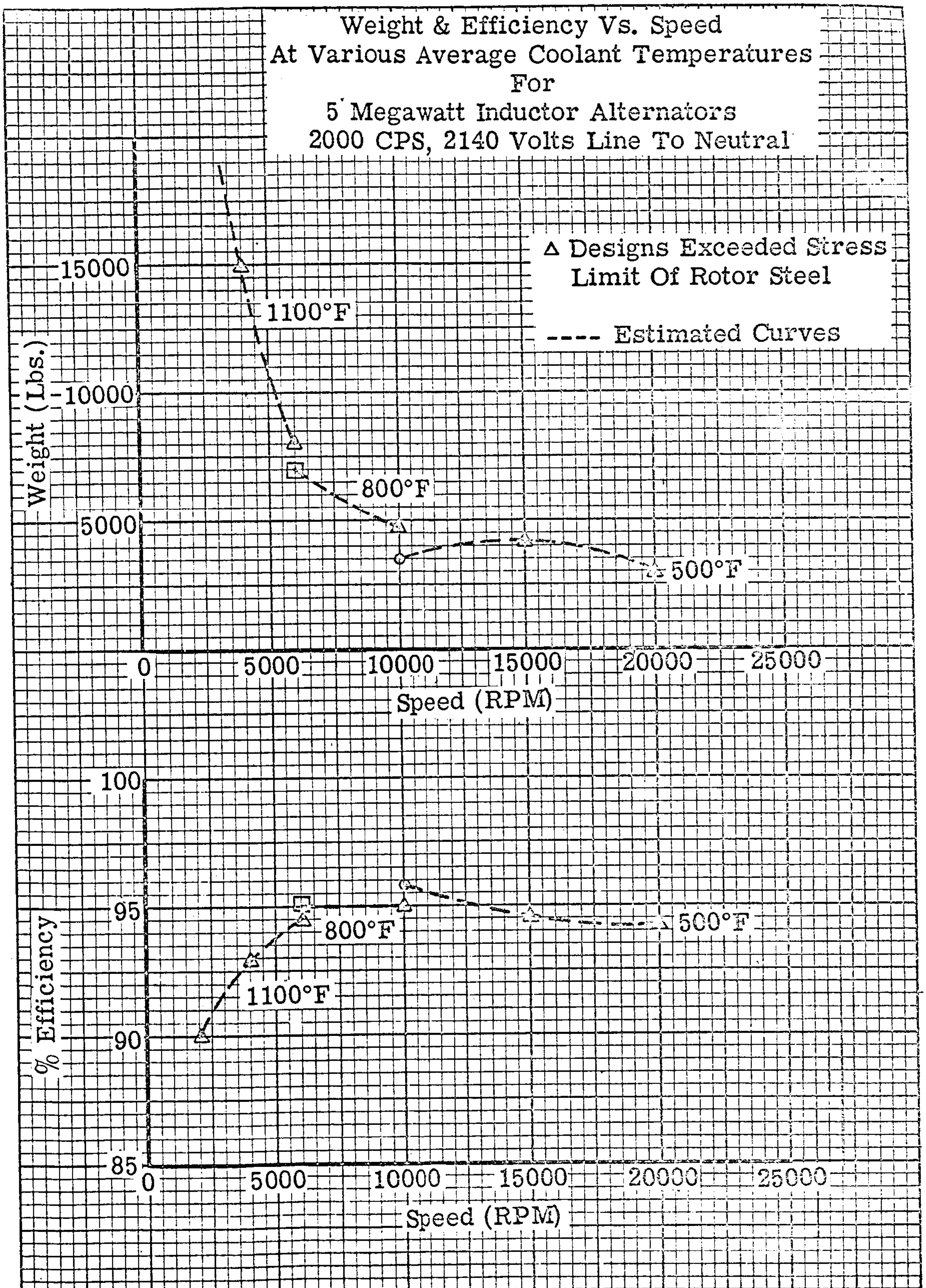

Weight & Efficiency Vs. Speed
At Various Average Coolant Temperatures
For
5 Megawatt Inductor Alternators
2000 CPS, 1500 Volts Line To Neutral
Δ Designs Exceeded Stress Limit Of Rotor Steel
---- Estimated Curves
Weight (Lbs.)
15000
10000
5000
0
5000
10000
15000
20000
25000
Speed (RPM)
1100°F
800°F
500°F
% Efficiency
100
95
90
85
0
5000
10000
15000
20000
25000
Speed (RPM)
800°F
500°F
1100°F

Figure 3. 1. 2-3



Weight & Efficiency Vs. Speed
At Various Average Coolant Temperatures
For
5 Megawatt Inductor Alternators
2000 CPS, 2140 Volts Line To Neutral
Δ Designs Exceeded Stress Limit Of Rotor Steel
---- Estimated Curves
Weight (Lbs.)
15000
10000
5000
0
5000
10000
15000
20000
25000
Speed (RPM)
1100°F
800°F
500°F
% Efficiency
100
95
90
85
0
5000
10000
15000
20000
25000
Speed (RPM)
800°F
1100°F
500°F

Figure 3. 1. 2-4

rotor-steel stress limits. As shown by Designs 142 thru 145, the weights of the 6000 RPM, 800°F designs were about twice the weights of the 10,000 and 15,000 RPM, 500°F designs.

All 1100°F designs, at 4000 RPM, exceed rotor-steel stress limits. Design 153, which approximately equaled the allowable rotor-stress limit, was about three times heavier than the 10,000 and 15,000 RPM, 500°F designs. All computer input data for 2000 RPM designs did not produce complete designs because the requirements for 120 poles at 2000 RPM limited the possible slot combinations. Designs 154 and 155 at 2000 RPM, 1100°F indicate the excessive weight resulting from this low speed.

Based upon the curves of weight vs. speed for five-megawatt generators, 500°F designs at speeds of 10,000 and 15,000 RPM are the lightest. To stay within the rotor-steel stress limits, 10,000 RPM appears preferrable for five-megawatt generators.

Efficiency vs. Speed Curves (Figures 3.1.2-1, 2, 3, and 4)
The highest efficiencies for five-megawatt generators occurred, in general, at 10,000 RPM, 500°F. At these conditions, all efficiencies were above 95% except for Design 127 (discussed in the preceding paragraph) which was excessively heavy and had high iron losses. The 15,000 RPM 500°F designs had efficiencies slightly less than the 10,000 RPM, 500°F designs, because the iron losses increased faster than the copper losses decreased at the higher speed. Windage losses at 500°F were negligible in comparison to the other losses.

Based upon the curves of Efficiency vs. Speed for five-megawatt generators, the highest efficiency designs occur at a speed of 10,000 RPM and a coolant temperature of 500°F.

Weight vs. Voltage Curves (Figures 3.1.2-5 through 3.1.2-9)
The weight vs. voltage curves at various speeds (figures 3.1.2-5, 6, and 7), show there is little variation in weight over the 500 to 2140 voltage range for the 10,000 RPM, 500°F designs. The 500 volt and the 1000 volt designs showed a slight weight advantage. The high weight of Design 127 appears to be due to a poor combination of design parameters, rather than directly due to the voltage level and its corresponding insulation requirements. As previously explained. the 1500 volt design weight could be brought in line with the other 10,000 RPM, 500°F weight by adjusting computer input data to obtain a higher X_d design.

The weight vs. voltage curves at various temperatures, (figures 3.1.2-8 and 9), illustrate the weight advantage of the practical lower-temperature designs. The 800°F, 6000 RPM designs show a greater effect of voltage on weight than do the 500°F, 10,000 RPM designs. The 500 volt, 800°F, 6000 RPM design showed a definite weight advantage over the higher voltage 800°F, 6000 RPM designs.

Based upon the weight vs. voltage curves, a five-megawatt generator voltage range of 500 to 1000 volts appears to give the lightest weight 10,000 RPM designs and a voltage of 1500 volts appears to produce the lightest weight 15,000 RPM designs.

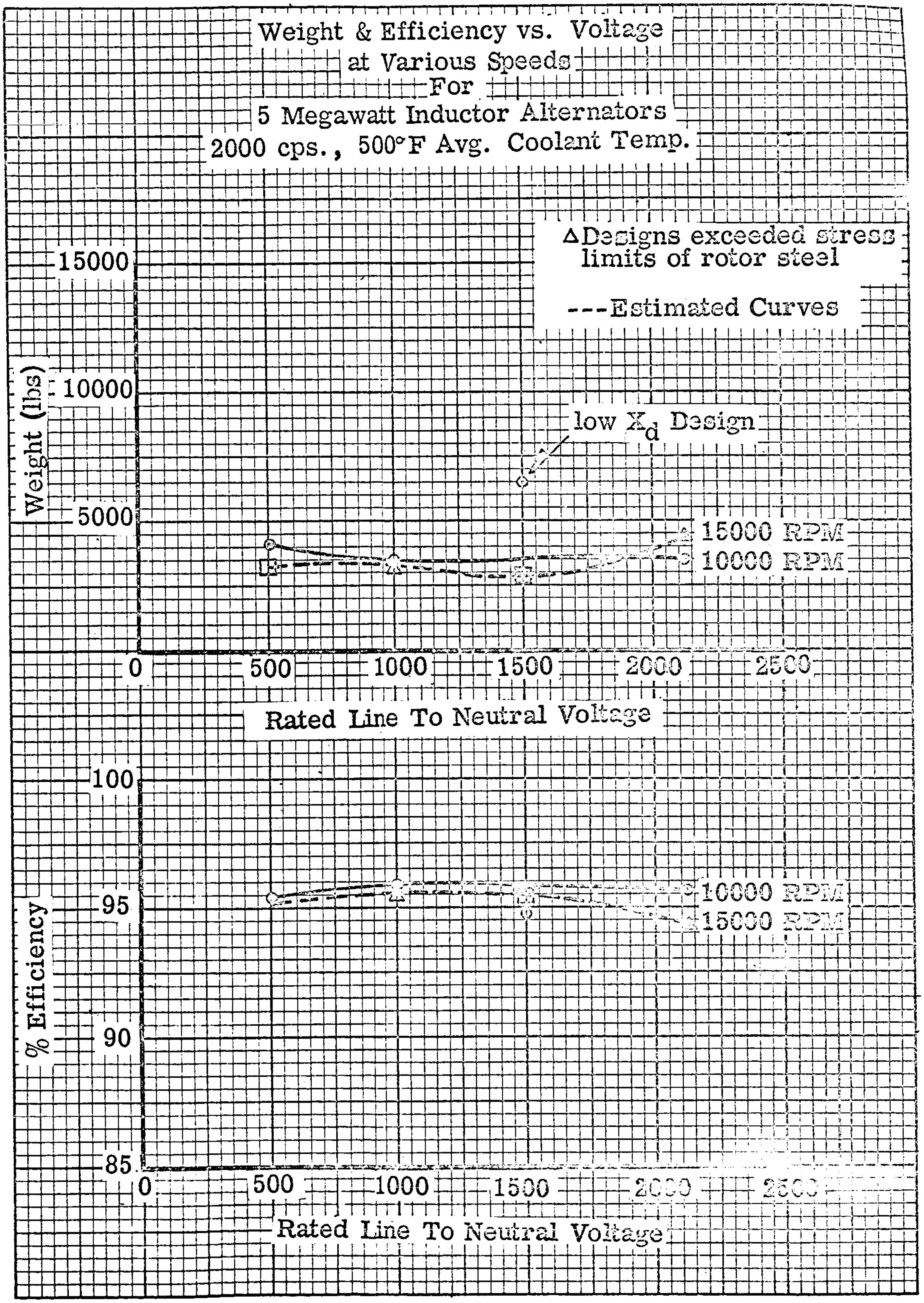

Weight & Efficiency vs. Voltage
at Various Speeds
For
5 Megawatt Inductor Alternators
2000 cps., 500°F Avg. Coolant Temp.
ΔDesigns exceeded stress limits of rotor steel
---Estimated Curves
Weight (lbs)
15000
10000
5000
low X_d Design
15000 RPM
10000 RPM
0
500
1000
1500
2000
2500
Rated Line To Neutral Voltage
% Efficiency
100
95
90
85
10000 RPM
15000 RPM
0
500
1000
1500
2000
2500
Rated Line To Neutral Voltage

Figure 3.1.2-5

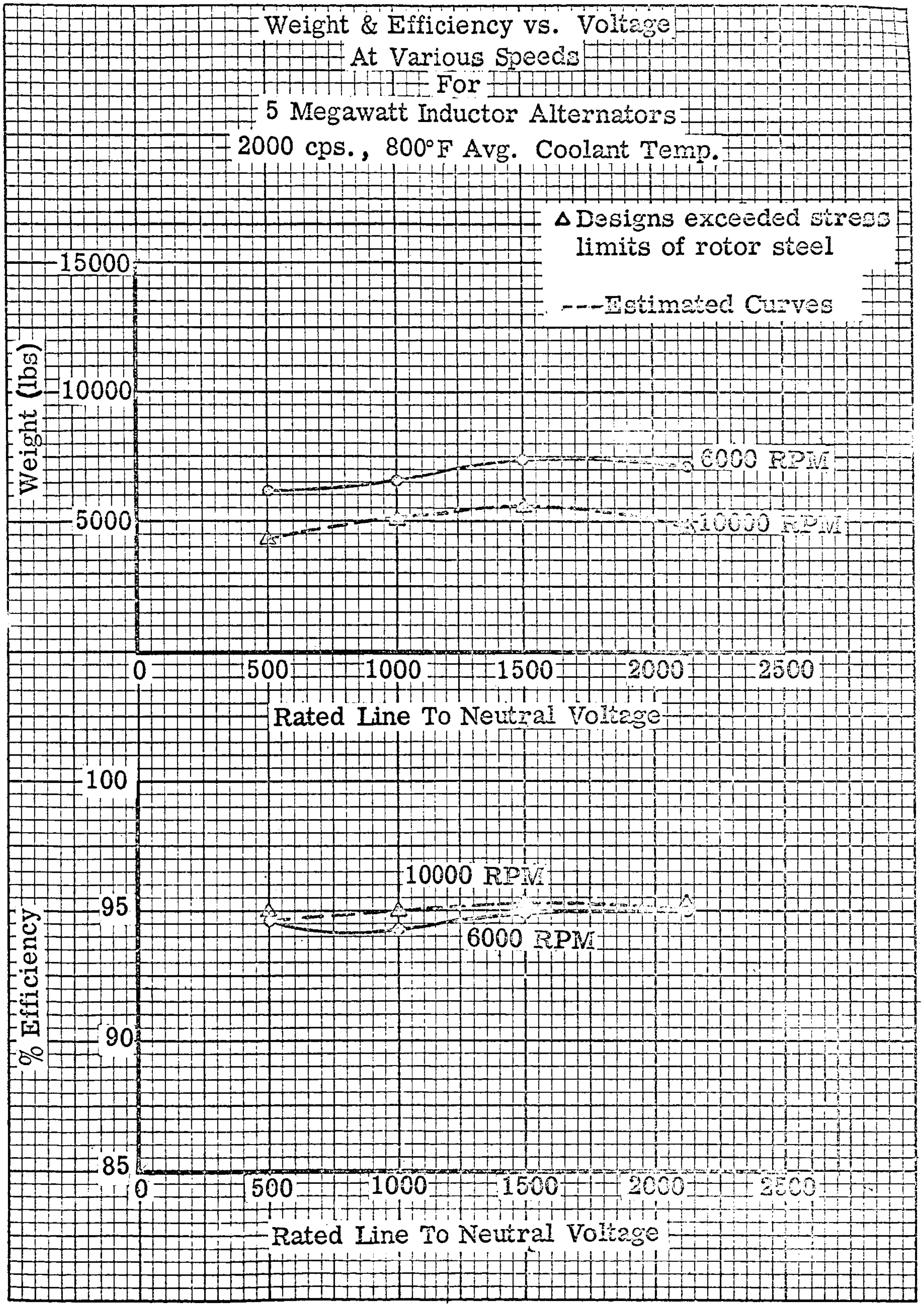
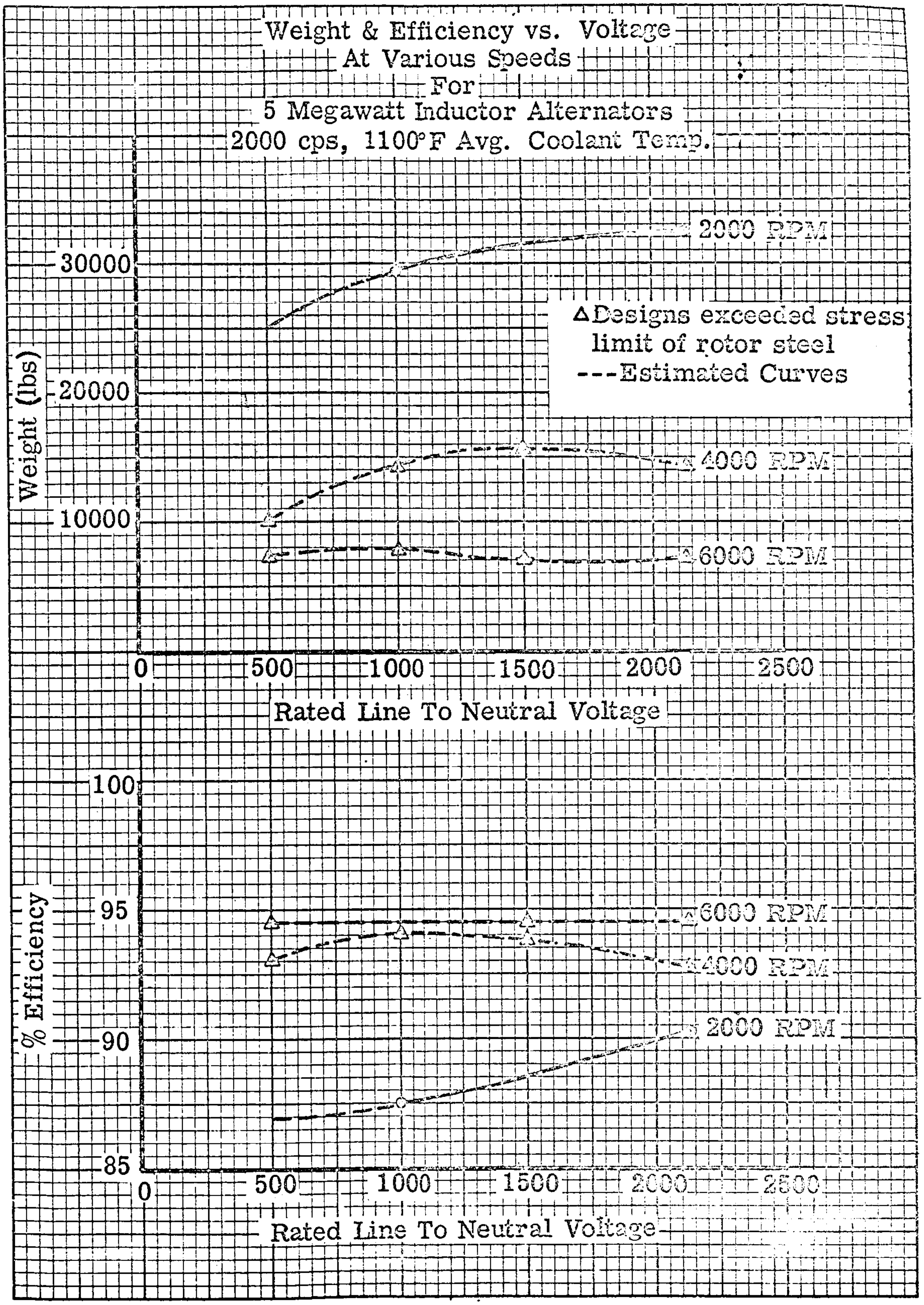

Weight & Efficiency vs. Voltage
At Various Speeds
For
5 Megawatt Inductor Alternators
2000 cps., 800°F Avg. Coolant Temp.
△ Designs exceeded stress limits of rotor steel
---Estimated Curves
Weight (lbs)
15000
10000
5000
6000 RPM
10000 RPM
0
500
1000
1500
2000
2500
Rated Line To Neutral Voltage
100
95
90
85
% Efficiency
10000 RPM
6000 RPM
0
500
1000
1500
2000
2500
Rated Line To Neutral Voltage

Figure 3.1.2-6



Weight & Efficiency vs. Voltage
At Various Speeds
For
5 Megawatt Inductor Alternators
2000 cps, 1100°F Avg. Coolant Temp.
Weight (lbs)
30000
20000
10000
2000 RPM
4000 RPM
6000 RPM
△Designs exceeded stress limit of rotor steel
---Estimated Curves
0
500
1000
1500
2000
2500
Rated Line To Neutral Voltage
% Efficiency
100
95
90
85
6000 RPM
4000 RPM
2000 RPM
0
500
1000
1500
2000
2500
Rated Line To Neutral Voltage

Figure 3.1.2-7

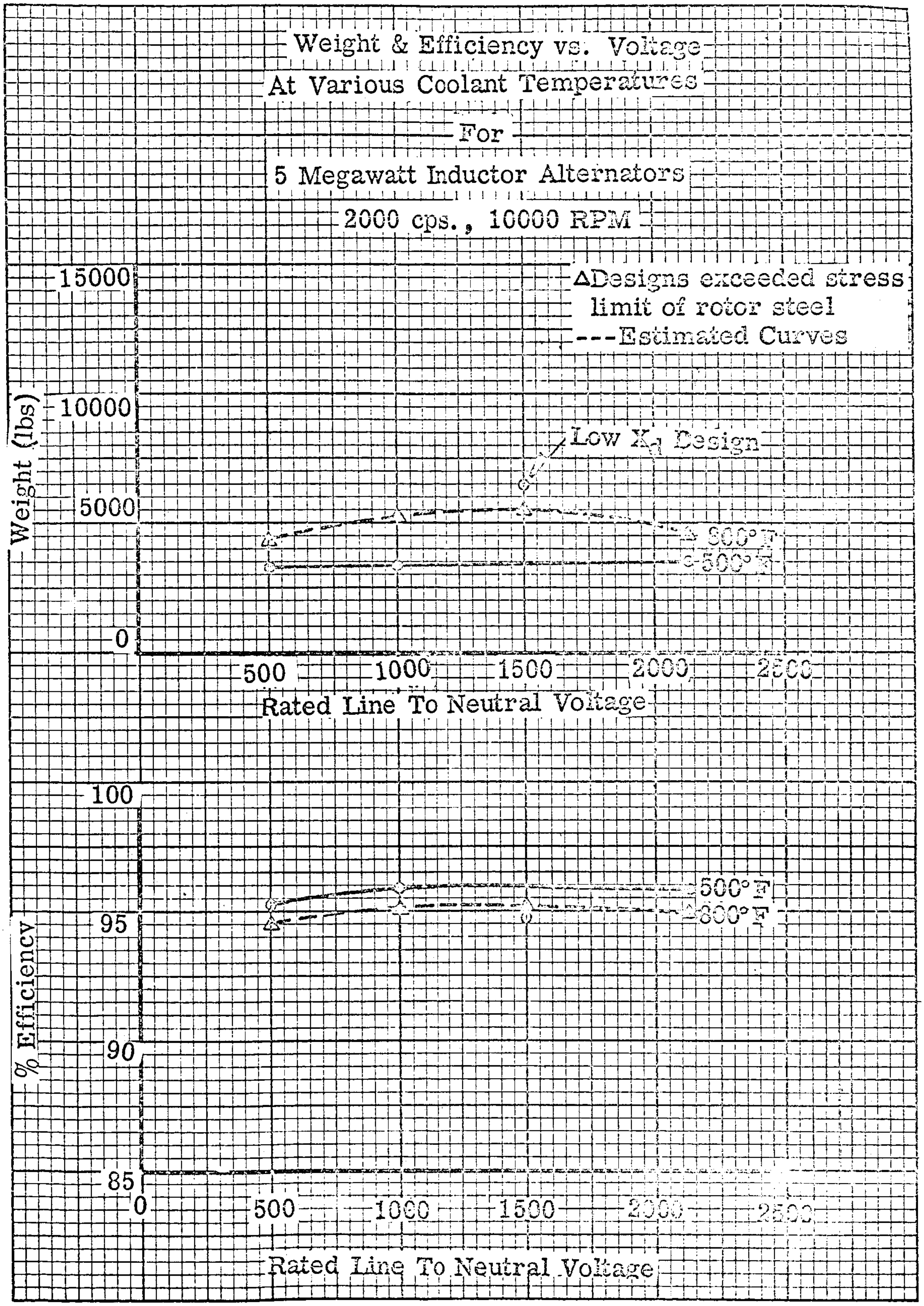

Weight & Efficiency vs. Voltage
At Various Coolant Temperatures
For
5 Megawatt Inductor Alternators
2000 cps., 10000 RPM
ΔDesigns exceeded stress limit of rotor steel
---Estimated Curves
Weight (lbs)
15000
10000
5000
0
Low X_d Design
800°F
500°F
500
1000
1500
2000
2500
Rated Line To Neutral Voltage
% Efficiency
100
95
90
85
0
500°F
800°F
500
1000
1500
2000
2500
Rated Line To Neutral Voltage

Figure 3.1.2-8

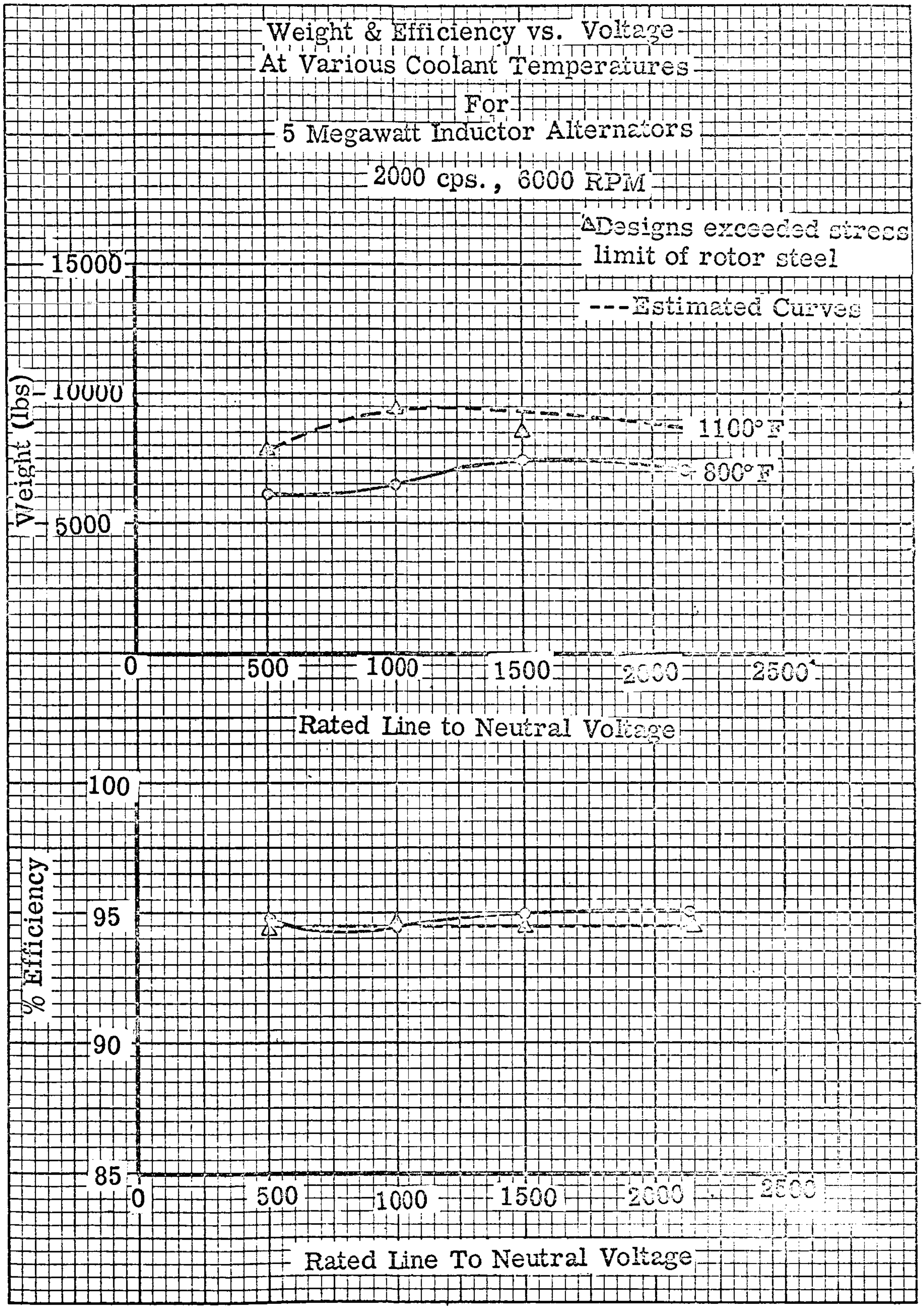

Weight & Efficiency vs. Voltage
At Various Coolant Temperatures
For
5 Megawatt Inductor Alternators
2000 cps., 6000 RPM
△Designs exceeded stress limit of rotor steel
---Estimated Curves
Weight (lbs)
15000
10000
5000
1100°F
800°F
0
500
1000
1500
2000
2500
Rated Line to Neutral Voltage
% Efficiency
100
95
90
85
0
500
1000
1500
2000
2500
Rated Line To Neutral Voltage

Figure 3.1.2-9

Efficiency vs. Voltage Curves (Figures 3.1.2-5 through 3.1.2-9)

In general, for the practical 10,000 RPM, 500°F designs, the voltage variation from 500 to 2140 volts had little effect on efficiency; however, a slight efficiency advantage is seen for voltages above 500 volts, since at 500 volts both the copper and iron losses were higher than for the other 10,000 RPM, 500°F designs (with the exception of design 127, the low X_d design previously discussed). Efficiencies of 95.8% were obtained for 10,000 RPM 500°F designs at both 1000 volts and 2140 volts.

Based on the efficiency vs. voltage curves, five-megawatt generator voltages of 1000 and 2140 volts result in 10,000 RPM, 500°F designs with the highest efficiencies. A voltage of 1500 volts resulted in the 15,000 RPM, 500°F design with an efficiency approximately equal to the most efficient 10,000 RPM, 500°F designs.

TABLE 3.1.2-1

5 Megawatt Generator Designs - 2000 cps

DE-SIGN NO.	AVG. COOL-ANT TEMP. (°F)	GEN. VOLTS L-N	% EFFI-CIENCY	GEN. WT. (LBS)	FIELD PWR. (KW)	LOSSES (KW) Fe = Iron Cu = Copper W = Windage			SIN-GLE STK LGTH (IN)	RO-TOR O.D. (IN)	MAX. GEN. O.D. (IN)	TO-TAL GEN LGTH (IN)	APPROX. AVG AC & FLD WDG. TEMP. RISE (°F)	P.U. X_d	MAX. ALLOW-ABLE ROTOR STRESS (psi)	ACTUAL MAX. ROTOR STRESS (psi)
						Fe	Cu	W								
						10,000 RPM										
126	500	2140	95.8	3539	11.0	150	68.9	.097	12.5	22.1	32.9	27.7	162	1.28	63700	30208
127	500	1500	94.8	6512	5.16	229	43.0	.236	17.5	26.6	37.4	39.1	117	.85	63700	43941
128	500	1000	95.8	3338	10.1	127	91.8	.089	12.6	21.6	31.8	29.0	152	1.39	63700	29086
129	500	500	95.3	3392	9.46	153	94.9	.096	12.7	22.0	32.1	29.4	182	1.43	63700	29866
130	800	2140	95.0	4777	8.28	156	97.9	7.26	12.3	26.8	37.0	28.5	177	1.35	30000	44686*
131	800	1500	95.3	5678	11.5	168	68.3	7.80	14.6	27.2	37.5	33.2	142	1.03	30000	46137*
132	800	1000	95.2	5094	6.90	173	68.6	8.47	12.5	27.7	37.7	29.3	149	1.07	30000	47637*
133	800	500	94.5	4426	7.87	196	85.1	7.36	11.6	26.9	36.8	27.5	197	1.32	30000	44554*
						15,000 RPM										
134	500	2140	94.5	4441	6.49	243	45.9	.336	16.0	22.4	33.1	36.1	162	1.01	63700	70134*
135	500	1500	95.7	2938	7.45	176	50.5	.235	11.8	20.8	30.8	27.9	172	1.15	63700	60317
136	500	1000	95.6	3438	6.01	190	38.4	.298	12.7	21.9	31.8	29.9	144	.99	63700	66685*
137	500	500	95.2	3132	6.71	207	47.2	.257	12.7	21.2	31.0	30.0	180	1.15	63700	62407

*Designs exceeded stress limit of rotor steel

TABLE 3.1.2-2

5 Megawatt Generator Designs - 2000 cps

DE-SIGN NO.	AVG. COOL-ANT TEMP. (°F)	GEN. VOLTS L-N	% EFFI-CIENCY	GEN. WT. (LBS)	FIELD PWR. (KW)	LOSSES (KW) Fe = Iron Cu = Copper W = Windage			SIN-GLE STK LGTH (IN)	RO-TOR O.D. (IN)	MAX. GEN. O.D. (IN)	TO-TAL GEN. LGTH (IN)	APPROX. AVG AC & FLD WDG TEMP. RISE (°F)	P.U. X_d	MAX ALLOW-ABLE ROTOR STRESS (psi)	ACTUAL MAX. ROTOR STRESS (psi)
						Fe	Cu	W								
20,000 RPM																
138	500	2140	94.2	3185	5.01	269	39.1	.575	12.3	21.1	31.2	29.5	215	1.20	63700	110465*
139	500	1500	94.9	3152	4.83	228	38.5	.582	12.1	21.2	31.1	28.9	207	1.29	63700	111084*
140	500	1000	93.5	3531	4.75	312	36.4	.664	13.3	21.8	31.7	29.9	215	1.07	63700	117219*
141	500	500	93.6	2551	5.13	295	46.7	.482	10.5	20.3	30.1	24.3	262	1.39	63700	102224*
6000 RPM																
142	800	2140	95.1	7174	9.75	149	103	3.28	14.5	30.9	41.7	33.5	142	1.24	30000	21405
143	800	1500	94.9	7454	8,60	146	117	3.50	14.7	31.3	42.0	33.0	142	1.11	30000	22046
144	800	1000	94.3	6670	9.74	145	154	3.14	13.7	30.6	41.1	31.0	159	1.35	30000	20967
145	800	500	94.6	6180	9.26	139	142	3.03	12.8	30.4	40.8	29.1	159	1.27	30000	20612
146	1100	2140	94.7	8097	13.3	109	143	29.4	15.6	31.5	42.7	34.7	176	1.35	11200	22238*
147	1100	1500	94.6	8295	12.8	106	152	29.7	16.2	31.5	42.5	35.8	163	1.22	11200	22329*
148	1100	1000	94.2	9159	12.4	121	154	35.0	17.5	32.7	43.1	38.8	174	1.43	11200	23776*
149	1100	500	94.5	7607	12.3	114	149	29.0	15.1	31.4	42.1	33.8	176	1.28	11200	21932*

*Designs exceeded stress limit of rotor steel

TABLE 3.1.2-3

5 Megawatt Generator Designs - 2000 cps

DE-SIGN NO.	AVG. COOL-ANT. TEMP. (°F)	GEN. VOLTS L-N	% EFFI-CIENCY	GEN. WT. (LBS)	FLD. PWR. (KW)	LOSSES (KW) Fe = Iron Cu = Copper W = Windage			SIN-GLE STK. LGTH. (IN)	RO-TOR O.D. (IN)	MAX. GEN. O.D. (IN)	TO-TAL GEN. LGTH. (IN)	APPROX. AVG. AC & FLD. WDG. TEMP. RISE (°F)	P.U. X_d	MAX. ALLW. ABLE ROTOR STRESS (psi)	ACTUAL MAX. ROTOR STRESS (psi)
						Fe	Cu	W								
4,000 RPM																
150	1100	2140	92.9	14820	17.5	144	215	21.4	21.0	37.6	49.7	45.2	164	1.12	11200	14109*
151	1100	1500	93.4	15699	16.5	141	191	22.3	22.1	38.0	49.9	47.4	137	1.02	11200	14376*
152	1100	1000	94.2	14412	16.2	110	180	19.0	21.7	36.7	48.2	46.9	147	1.08	11200	13449*
153	1100	500	93.2	9997	24.0	118	234	13.7	16.5	34.2	45.9	36.7	172	1.46	11200	11619*
2,000 RPM																
154	1100	2140	90.1	32892	39.3	210	328	10.6	27.2	49.3	64.0	57.3	172	1.15	11200	6125
155	1100	1000	87.4	29002	48.2	173	536	9.35	24.8	48.0	62.3	52.3	182	1.57	11200	5831

*Designs exceeded stress limit of rotor steel

3.1.3 Ten-Megawatt Generator Designs

Summary

The weight and efficiency vs. speed curves indicate the desirability of 10,000 RPM generators operating at an average coolant temperature of 500°F. All ten-megawatt generator designs for speeds above 10,000 RPM exceeded the stress limit of the rotor steel.

In order not to exceed the rotor stress limits it was necessary to reduce the speed to 4000 RPM for 800°F designs and to 2000 RPM for 1100°F designs. The resulting low speed designs were several times heavier than the 10,000 RPM, 500°F designs.

The weight and efficiency vs. voltage curves for the 10-megawatt generators show a weight advantage at 500 and 1500 volts, with the highest efficiency occurring at 1500 and 2140 volts for the practical 10,000 RPM, 500°F designs.

The following table is a summary of the ten-megawatt designs in order of increasing weight and decreasing efficiency.

DESIGN	ELECTRICAL WEIGHT	DESIGN	% EFF.
500 V, 10,000 RPM, 500°F	7039 Lbs.	1500 V, 10,000 RPM, 500°F	95.8
1500 V, 10,000 RPM, 500°F	7215 Lbs.	2140 V, 10,000 RPM, 500°F	95.7
2140 V, 10,000 RPM, 500°F	8503 Lbs.	1000 V, 10,000 RPM, 500°F	95.00
1000 V, 10,000 RPM, 500°F	8836 Lbs.	500 V, 10,000 RPM, 500°F	91.1

Combining like design points, the best ten-megawatt designs are:

1500 V, 10,000 RPM, 500°F	7215 Lbs.	95.8% Eff.
2140 V, 10,000 RPM, 500°F	8503 Lbs.	95.7% Eff.

Weight vs. Speed Curves (Figures 3.1.3-1, 2, 3 and 4)

At an average coolant temperature of 500°F, the highest ten-megawatt generator speed possible without exceeding the stress limit of the rotor steel, was 10,000 RPM. The 15,000 RPM, 500°F, ten-megawatt designs exceeded the maximum rotor stress limit by 30% or more. (See Designs 166 thru 169)

At an average coolant temperature of 800°F, 10,000 RPM, ten-megawatt designs showed over twice the rotor stress allowable at this temperature. A speed of 6000 RPM produced designs with rotor stresses at or above the allowable stress. These 6000 RPM, 800°F designs were more than 50% heavier than the 10,000 RPM, 500°F designs. 4000 RPM, 800°F designs were found to be more than twice the weight of the 10,000 RPM, 500°F designs.

Based upon the ten-megawatt designs calculated, the 10,000 RPM, 500°F designs are the best, from a weight standpoint, for this rating.

Efficiency vs. Speed Curves. (Figures 3.1.3-1, 2, 3 and 4).

At an average coolant temperature of 500°F and a speed of 10,000 RPM, efficiencies greater than 95% were obtained for the 1000, 1500, and 2140 volt designs. The efficiency of 91.1% obtained for the 500 volt design resulted from the higher iron losses, as can be seen by comparing the tabulated data for Design 161 with those of Designs 158, 159, and 160. Design 161 used 54 slots compared with over 100 slots for the other three designs; the air gap flux density was also approximately 70% higher in Design 161. Because the pole face loss is proportional to the tooth width raised to the 1.88 power and proportional to the square of air gap flux density, Design 161 had three times more pole face

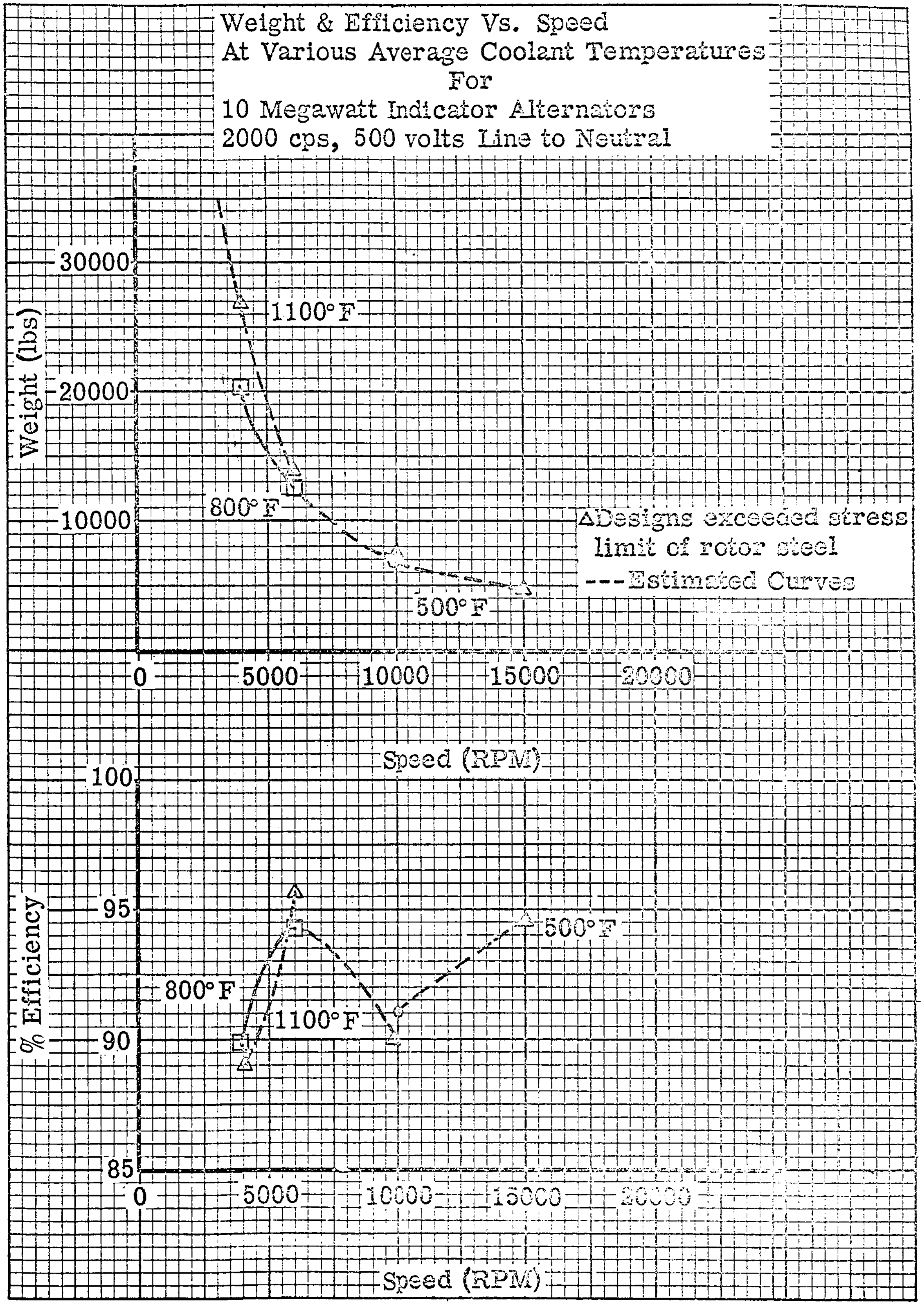
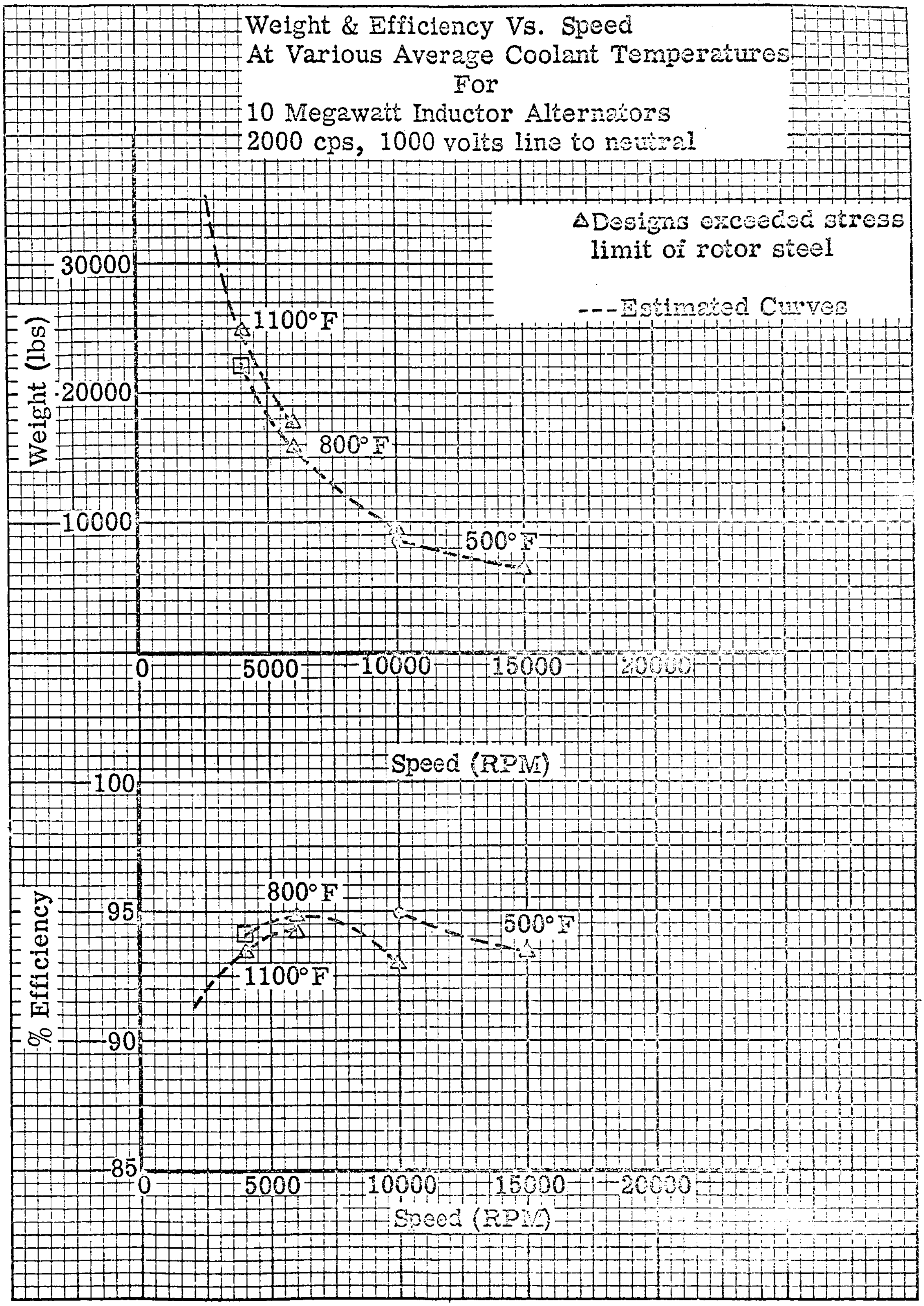

Weight & Efficiency Vs. Speed
At Various Average Coolant Temperatures
For
10 Megawatt Indicator Alternators
2000 cps, 500 volts Line to Neutral
Weight (lbs)
30000
20000
10000
1100° F
800° F
500° F
△Designs exceeded stress limit of rotor steel
---Estimated Curves
0
5000
10000
15000
20000
Speed (RPM)
% Efficiency
100
95
90
85
800° F
1100° F
500° F
0
5000
10000
15000
20000
Speed (RPM)

Figure 3.1.3-1



Weight & Efficiency Vs. Speed
At Various Average Coolant Temperatures
For
10 Megawatt Inductor Alternators
2000 cps, 1000 volts line to neutral
△Designs exceeded stress limit of rotor steel
---Estimated Curves
Weight (lbs)
30000
20000
10000
1100°F
800°F
500°F
0
5000
10000
15000
20000
Speed (RPM)
% Efficiency
100
95
90
85
800°F
500°F
1100°F
0
5000
10000
15000
20000
Speed (RPM)

Figure 3.1.3-2

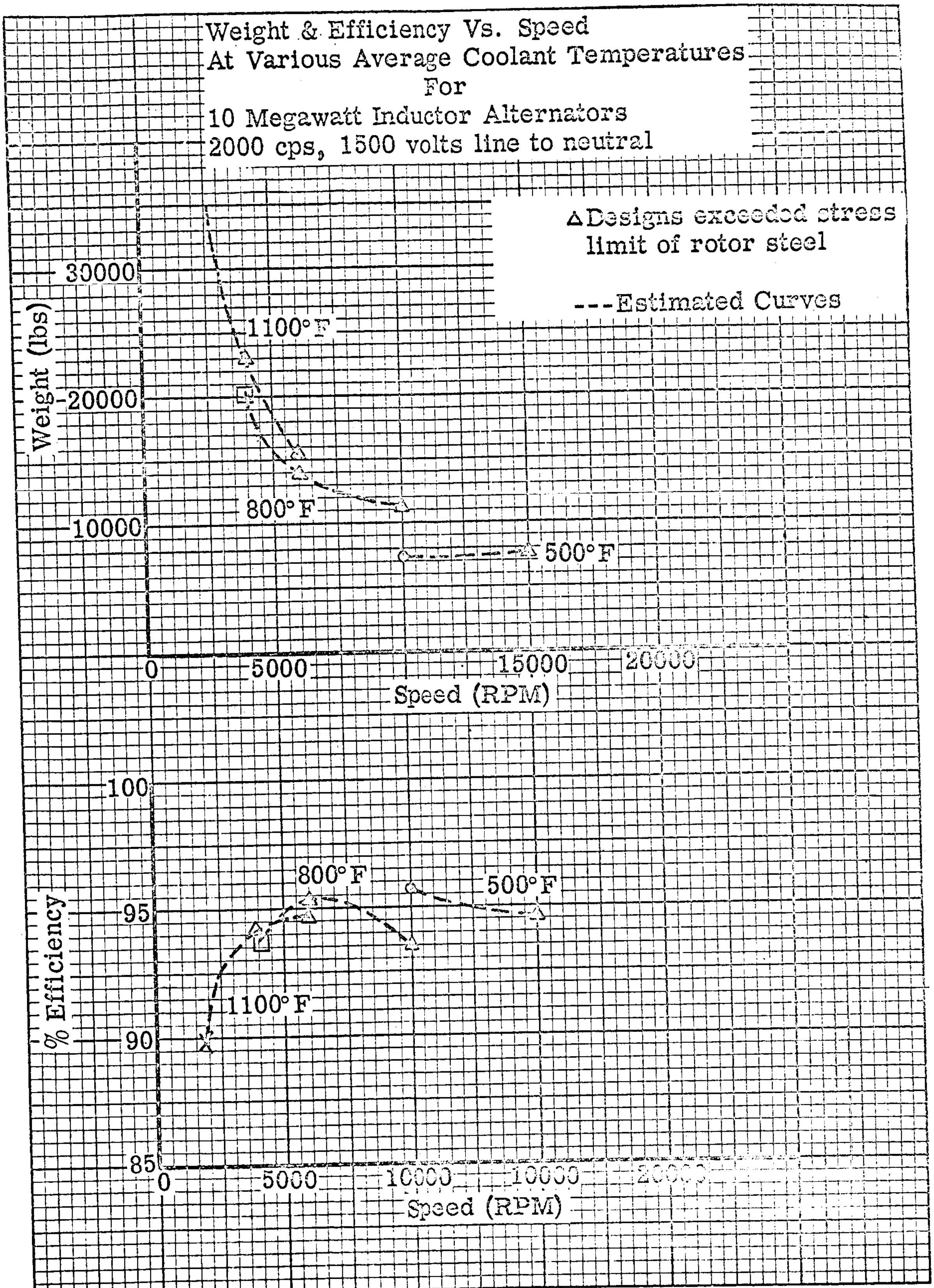

Weight & Efficiency Vs. Speed
At Various Average Coolant Temperatures
For
10 Megawatt Inductor Alternators
2000 cps, 1500 volts line to neutral
Designs exceeded stress limit of rotor steel
---Estimated Curves
Weight (lbs)
30000
20000
10000
1100° F
800° F
500° F
0
5000
15000
20000
Speed (RPM)
% Efficiency
100
95
90
85
800° F
500° F
1100° F
0
5000
10000
Speed (RPM)

Figure 3. 1. 3-3

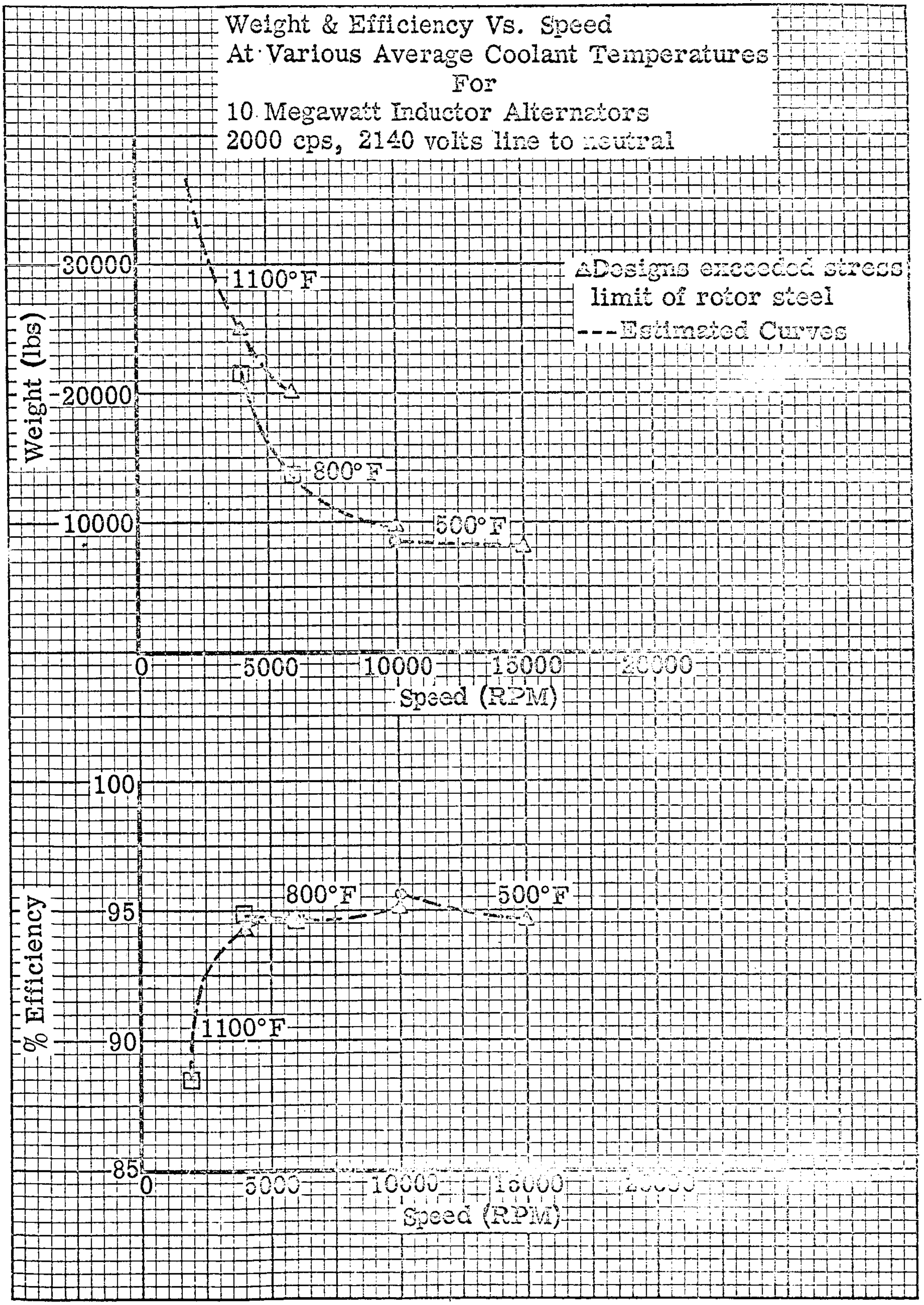

Weight & Efficiency Vs. Speed
At Various Average Coolant Temperatures
For
10 Megawatt Inductor Alternators
2000 cps, 2140 volts line to neutral
△Designs exceeded stress limit of rotor steel
---Estimated Curves
Weight (lbs)
30000
20000
10000
1100°F
800°F
500°F
0
5000
10000
15000
20000
Speed (RPM)
% Efficiency
100
95
90
85
800°F
500°F
1100°F
0
5000
10000
15000
Speed (RPM)

Figure 3. 1. 3-4

loss than Design 160 with 100 slots, and about six times more pole face loss than Designs 158 and 159 with 216 and 180 slots respectively.

Based on the Efficiency vs. Speed Curves, for the 10-megawatt designs, a speed of 10,000 RPM gives the highest efficiency for generator voltages of 1000 volts to 2140 volts.

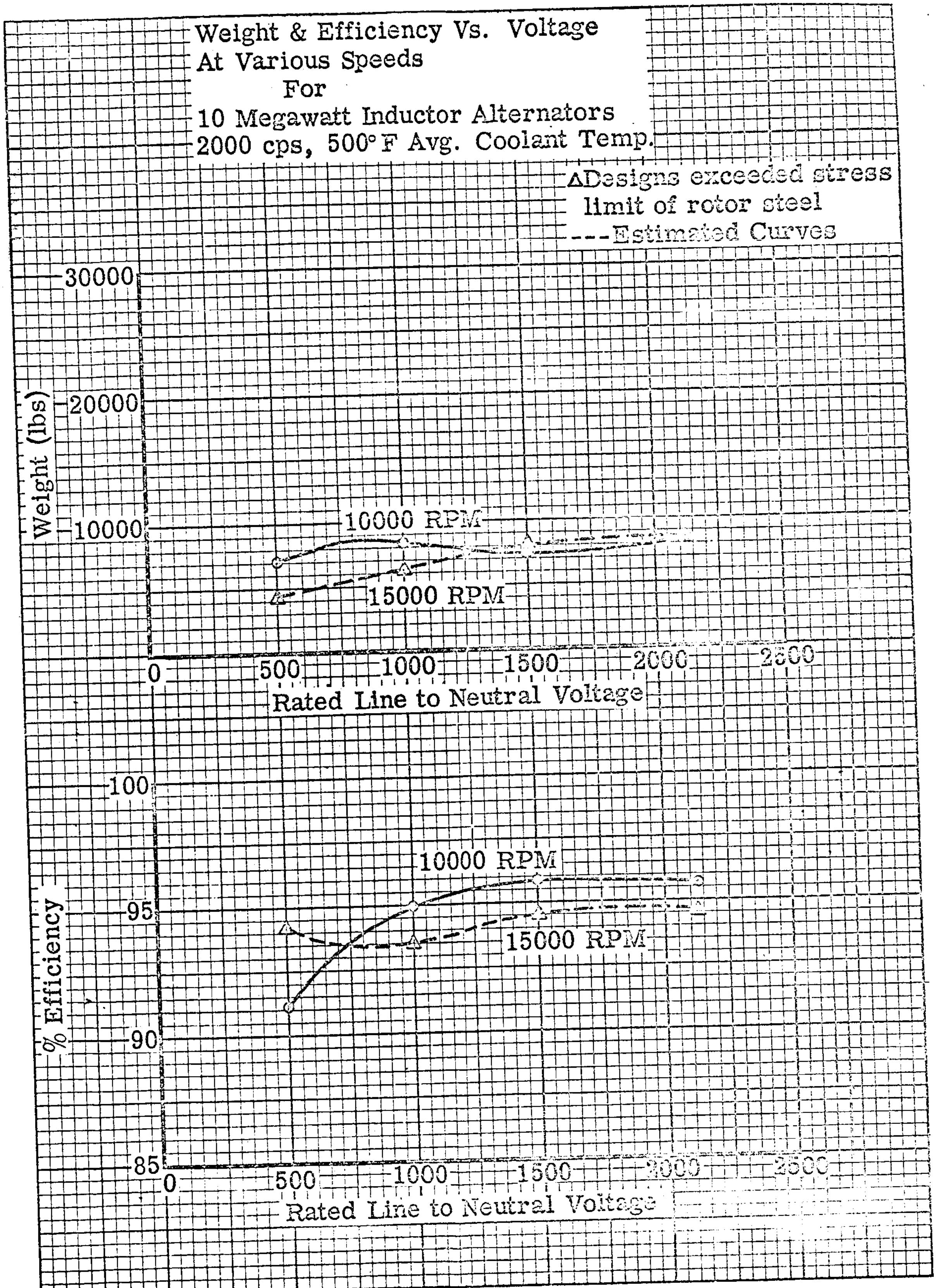
<u>Weight vs. Voltage Curves</u> (Figures 3.1.3-5 through 3.1.3-10).

Figures 3.1.3-5 and -8 show a weight advantage of 500 and 1500 volts for the practical 10,000 RPM, 500°F designs. This indicates that this condition gives the best combinations of internal generator parameters. The 500 volt design showed a slight (3%) weight advantage over the 1500 volt design.

Figures 3.1.3-6 and -10 show a weight advantage at 500 and 1500 volts for the practical 4000 RPM, 800°F designs. Designs 179 and 181 show that the weights are almost identical at these voltages.

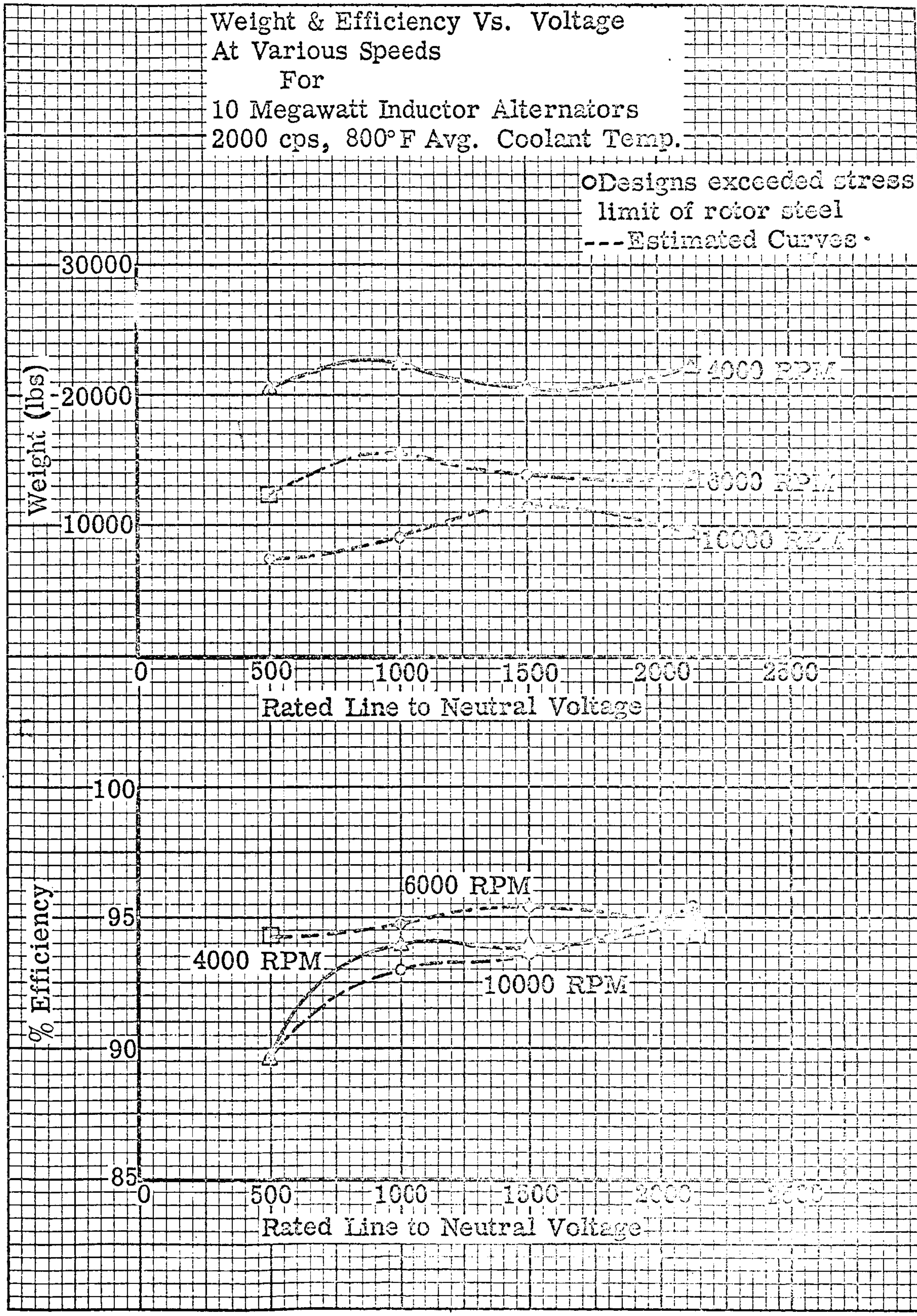
The only 2000 RPM, 1100°F designs found practical show that the 2140 volt design offers a slight weight advantage over the 1500 volt design. The weight required by this low speed was more than 8 times the weight of the 10,000 RPM, 500°F designs.

Based upon the weight vs. voltage curves, the 500 and 1500 volt designs appear to be the best from a weight standpoint.



Weight & Efficiency Vs. Voltage
At Various Speeds
For
10 Megawatt Inductor Alternators
2000 cps, 500° F Avg. Coolant Temp.
ΔDesigns exceeded stress limit of rotor steel
---Estimated Curves
30000
20000
10000
Weight (lbs)
10000 RPM
15000 RPM
0
500
1000
1500
2000
2500
Rated Line to Neutral Voltage
100
95
90
85
% Efficiency
10000 RPM
15000 RPM
0
500
1000
1500
2000
2500
Rated Line to Neutral Voltage

Figure 3. 1. 3-5



Weight & Efficiency Vs. Voltage
At Various Speeds
For
10 Megawatt Inductor Alternators
2000 cps, 800°F Avg. Coolant Temp.
○Designs exceeded stress limit of rotor steel
---Estimated Curves
Weight (lbs)
30000
20000
10000
0
500
1000
1500
2000
2500
Rated Line to Neutral Voltage
4000 RPM
6000 RPM
10000 RPM
% Efficiency
100
95
90
85
0
500
1000
1500
2000
2500
Rated Line to Neutral Voltage
6000 RPM
4000 RPM
10000 RPM

Figure 3. 1. 3-6

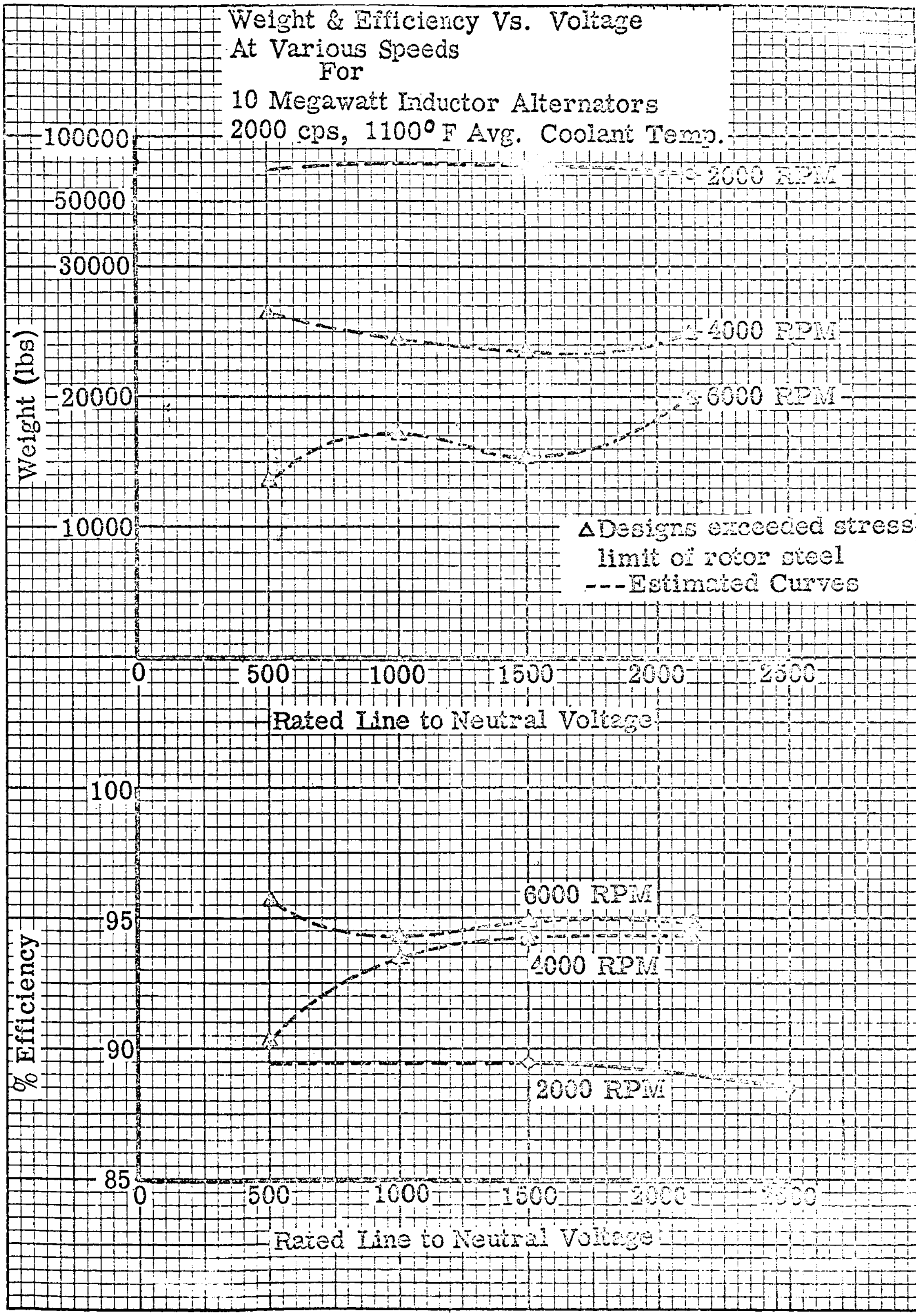
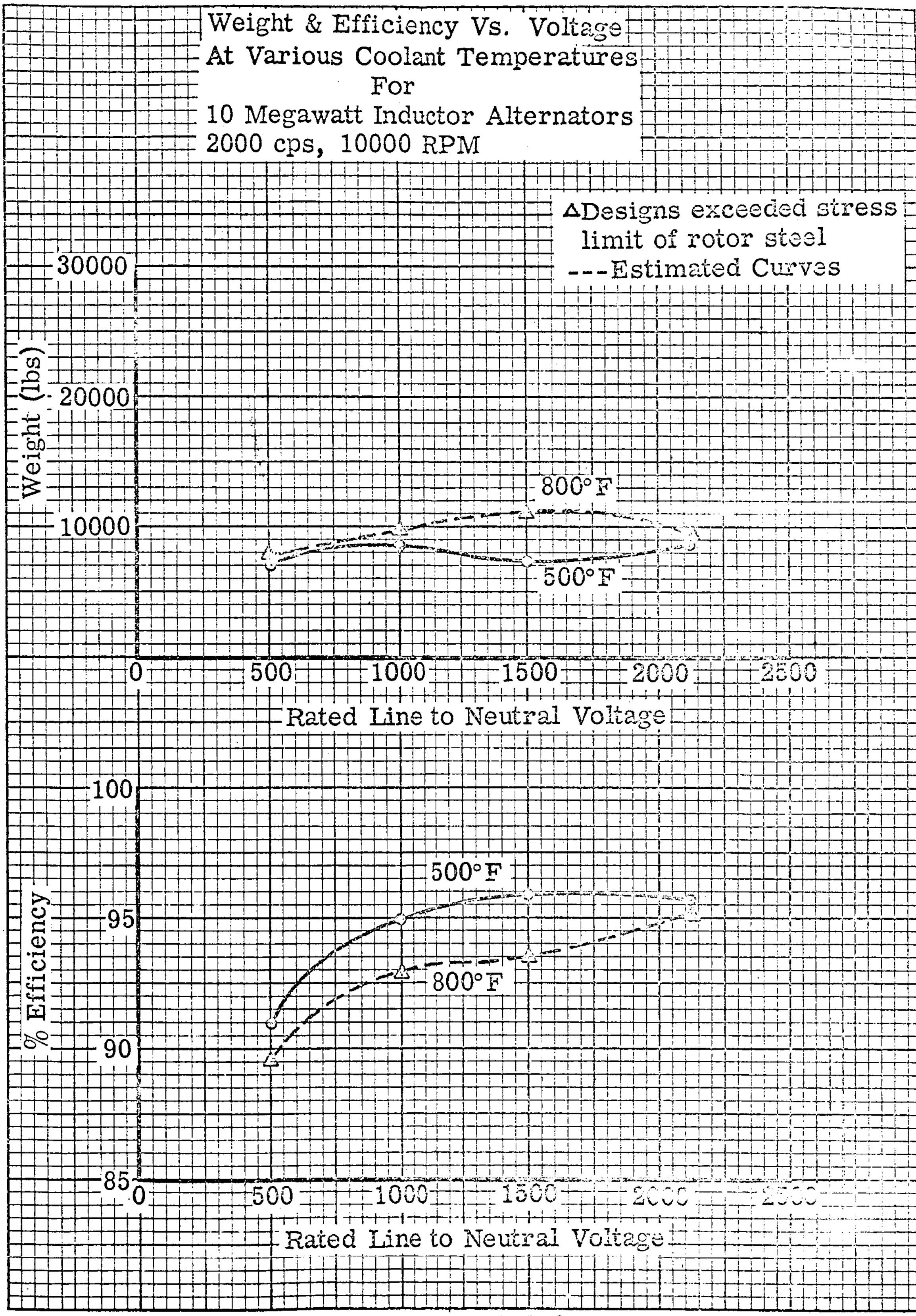

Weight & Efficiency Vs. Voltage
At Various Speeds
For
10 Megawatt Inductor Alternators
2000 cps, 1100° F Avg. Coolant Temp.
100000
50000
30000
20000
10000
Weight (lbs)
2000 RPM
4000 RPM
6000 RPM
△Designs exceeded stress limit of rotor steel
---Estimated Curves
0
500
1000
1500
2000
2500
Rated Line to Neutral Voltage
100
95
90
85
% Efficiency
6000 RPM
4000 RPM
2000 RPM
0
500
1000
1500
2000
Rated Line to Neutral Voltage

Figure 3.1.3-7



Weight & Efficiency Vs. Voltage
At Various Coolant Temperatures
For
10 Megawatt Inductor Alternators
2000 cps, 10000 RPM
ΔDesigns exceeded stress limit of rotor steel
---Estimated Curves
Weight (lbs)
30000
20000
10000
800°F
500°F
0
500
1000
1500
2000
2500
Rated Line to Neutral Voltage
% Efficiency
100
95
90
85
500°F
800°F
0
500
1000
1500
2000
2500
Rated Line to Neutral Voltage

Figure 3. 1. 3-8

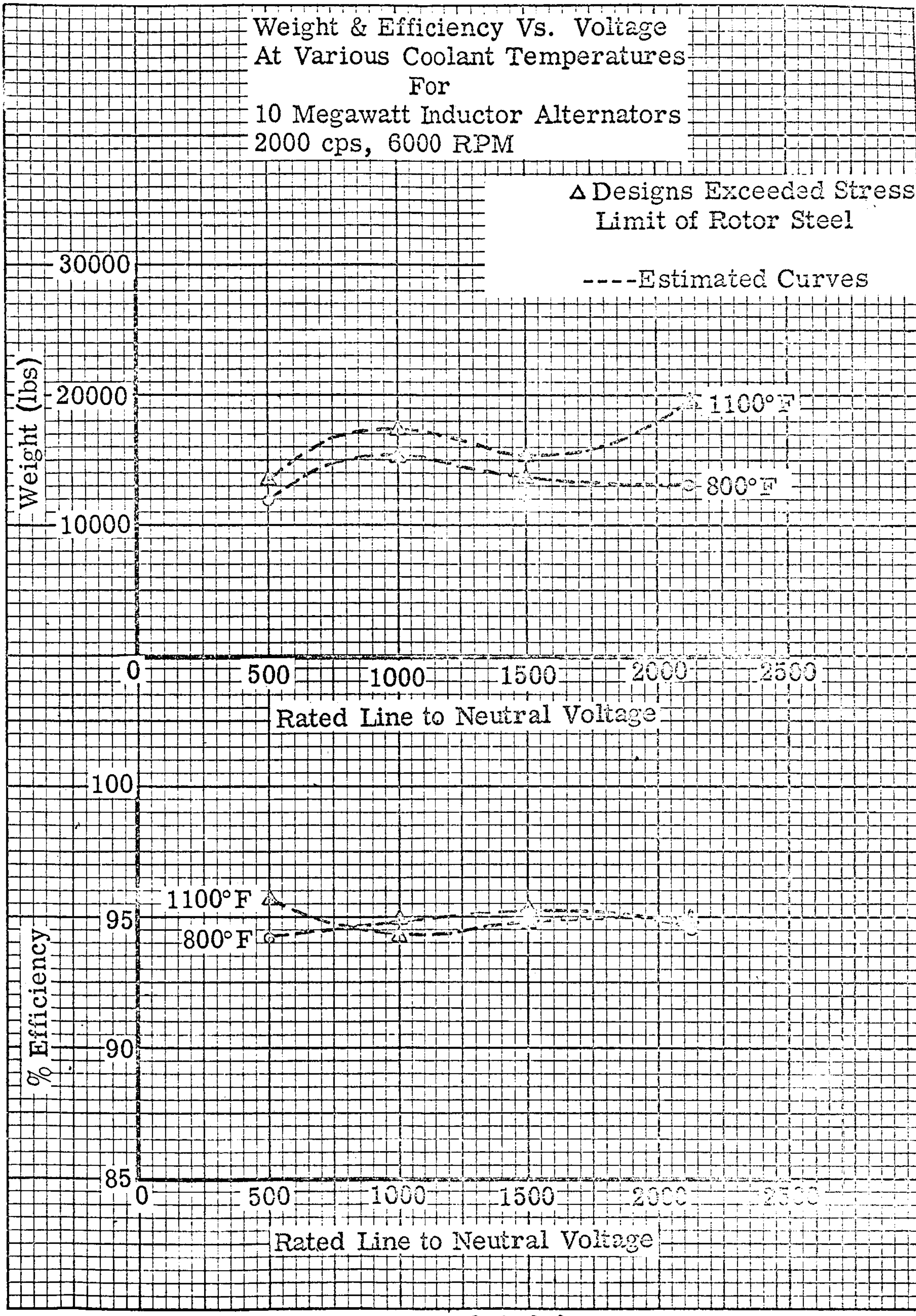

Weight & Efficiency Vs. Voltage
At Various Coolant Temperatures
For
10 Megawatt Inductor Alternators
2000 cps, 6000 RPM
Δ Designs Exceeded Stress Limit of Rotor Steel
----Estimated Curves
Weight (lbs)
30000
20000
10000
0
500
1000
1500
2000
2500
1100°F
800°F
Rated Line to Neutral Voltage
% Efficiency
100
95
90
85
1100°F
800°F
0
500
1000
1500
2000
2500
Rated Line to Neutral Voltage

Figure 3. 1. 3-9

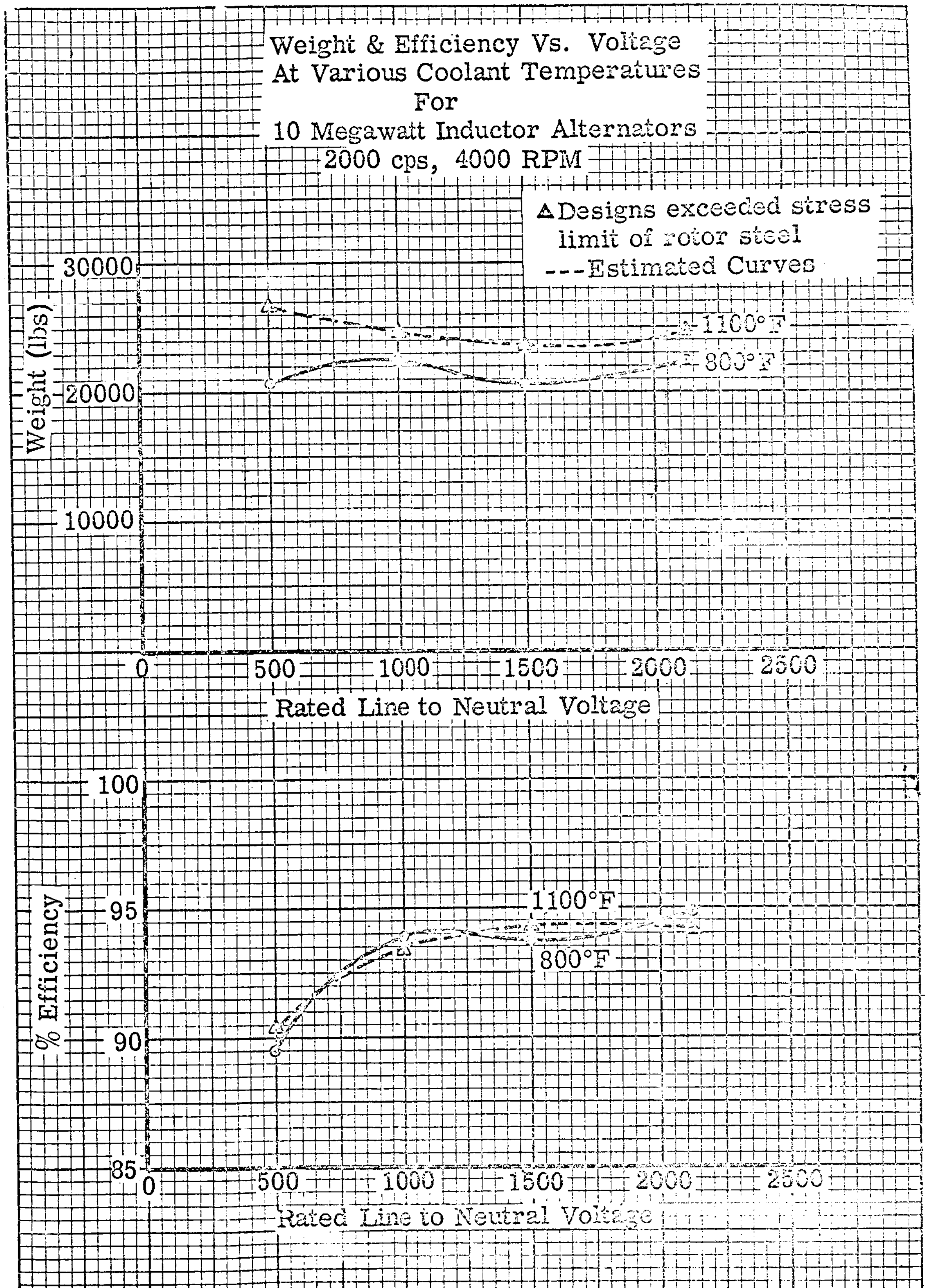


Figure 3. 1. 3-10

Efficiency vs. Voltage Curves (Figures 3.1.3-5 through 3.1.3-10).

Figures 3.1.3-5 and -8 show the highest efficiencies at the 1500 and 2140 volt designs for the 10,000 RPM, 500°F condition due to the lower iron losses of the higher-voltage designs. Considerably lower efficiencies are evident for the 500 volt designs both at 10,000 RPM, 500°F and at 4000 RPM, 800°F. In both cases, the iron losses for the 500 volt designs were two to three times the iron losses at the higher voltage designs. The iron losses were high because there were less slots resulting in increased pole face losses.

Based upon the efficiency vs. voltage curves for the 10-megawatt-generator designs, the efficiency is highest for the 1500 and 2140 volt designs.

TABLE 3.1.3-1

10 Megawatt Generator Designs - 2000 cps

DE-SIGN NO.	AVG. COOL-ANT TEMP. (^oF)	GEN. VOLTS. L-N	% EFFI-CIENCY	GEN. WT. (LBS)	FLD. PWR. (KW)	LOSSES (KW) Fe = Iron Cu = Copper W = Windage			SIN-GLE STK. LGTH. (IN)	RO-TOR O.D. (IN)	MAX. GEN. O.D. (IN)	TO-TAL GEN. LGTH. (IN)	APPROX. AVG. AC & FLD. WDG. TEMP. RISE (^oF)	P.U. X_d	MAX. ALLOW-ABLE ROTOR STRESS (psi)	ACTUAL MAX. ROTOR STRESS (psi)
						Fe	Cu	W								
10,000 RPM																
158	500	2140	95.7	8503	12.1	338	110	.334	18.8	28.6	40.9	41.8	182	1.15	63700	51004
159	500	1500	95.8	7215	11.9	301	141	.271	17.3	27.4	39.2	38.8	197	1.43	63700	46592
160	500	1000	95.0	8836	11.8	422	104	.341	20.4	28.8	40.5	45.4	179	1.24	63700	51001
161	500	500	91.1	7039	11.5	839	133	.392	13.1	29.6	42.7	30.6	394	1.20	63700	54373
162	800	2140	95.3	9486	10.2	339	129	21.8	15.4	33.9	45.5	34.9	212	1.34	30000	71665*
163	800	1500	93.5	11449	9.39	578	85.7	34.0	15.8	37.2	49.1	36.2	202	.91	30000	86298*
164	800	1000	93.0	9137	9.70	625	94.8	27.4	13.2	35.5	47.5	31.0	242	.95	30000	78456*
165	800	500	89.7	7302	15.3	985	139	23.4	10.0	34.4	47.0	24.5	517	1.08	30000	73786*
15,000 RPM																
166	500	2140	94.6	8428	7.20	497	68.4	1.06	18.5	28.6	40.7	41.4	232	1.17	63700	114505*
167	500	1500	94.6	7826	9.71	511	63.5	.945	18.6	27.9	39.4	42.1	215	1.06	63700	108384*
168	500	1000	93.3	6293	15.2	652	60.8	1.09	12.9	28.8	40.9	30.5	307	.82	63700	115317*
169	500	500	94.2	4520	10.8	510	105	.537	12.4	24.8	36.1	29.7	342	1.46	63700	84935*

*Designs exceeded stress limit of rotor steel

TABLE 3.1.3-2

10 Megawatt Generator Designs - 2000 cps

DE-SIGN NO.	AVG. COOL-ANT TEMP. (°F)	GEN. VOLTS L-N	% EFFI-CIENCY	GEN. WT. (LBS)	FLD. PWR. (KW)	LOSSES (KW) Fe = Iron Cu = Copper W = Windage			SIN-GLE STK. LGTH. (IN)	RO-TOR O.D. (IN)	MAX. GEN. O.D. (IN)	TO-TAL GEN. LGTH. (IN)	APPROX. AVG. AC & FLD. WDG. TEMP. RISE (°F)	P.U. X_d	MAX. ALLOW-ABLE ROTOR STRESS (psi)	ACTUAL MAX. ROTOR STRESS (psi)
						Fe	Cu	W								
6,000 RPM																
170	800	2140	94.6	13349	13.7	292	266	8.03	18.5	37.3	49.5	40.8	232	1.50	30000	31433 **
171	800	1500	95.3	13689	12.6	280	208	8.62	18.2	37.9	50.2	40.1	177	1.25	30000	32528 *
172	800	1000	94.8	15812	12.0	364	169	10.4	20.1	39.4	51.7	44.2	186	1.05	30000	34961 *
173	800	500	94.3	12222	13.4	368	234	7.64	17.7	37.0	48.7	39.5	237	1.48	30000	30422 **
174	1100	2140	94.8	19976	16.6	249	191	110	22.5	41.6	54.7	48.3	210	1.02	11200	39234 *
175	1100	1500	94.9	15122	17.2	205	253	78.6	19.1	38.7	51.5	41.7	210	1.33	11200	34039 *
176	1100	1000	94.3	17436	15.9	284	121	95.2	21.0	40.4	53.1	45.7	210	1.12	11200	36682 *
177	1100	500	95.7	13173	22.1	287	216	59.4	18.2	36.5	49.2	40.3	210	1.43	11200	30269 *
4,000 RPM																
178	800	2140	94.9	22155	15.7	302	218	5.21	22.8	43.6	57.0	48.1	150	1.03	30000	19203
179	800	1500	93.7	20507	16.9	293	370	4.77	22.0	42.7	55.8	47.3	184	1.35	30000	18435
180	800	1000	94.0	22512	16.4	337	296	5.23	23.9	43.6	56.5	51.4	186	1.29	30000	19039
181	800	500	89.6	20559	22.5	922	232	7.91	16.4	47.6	62.6	36.4	257	1.05	30000	22861

*Designs exceeded stress limit of rotor steel
**Designs approximately equaled stress limit of rotor steel

TABLE 3.1.3-3

10 Megawatt Generator Designs - 2000 cps

DE-SIGN NO.	AVG. COOL-ANT TEMP. (°F)	GEN. VOLTS L-N	% EFFI-CIENCY	GEN. WT. (LBS)	FLD. PWR. (KW)	LOSSES (KW) Fe = Iron Cu = Copper W = Windage			SIN-GLE STK. LGTH. (IN)	RO-TOR O.D. (IN)	MAX. GEN. O.D. (IN)	TO-TAL GEN. LGTH. (IN)	APPROX. AVG. AC & FLD. WDG. TEMP. RISE (°F)	P.U. X_d	MAX. ALLOW-ABLE ROTOR STRESS (psi)	ACTUAL MAX. ROTOR STRESS (psi)
						Fe	Cu	W								
4,000 RPM																
182	1100	2140	94.4	24923	22.8	220	327	48.0	24.4	44.6	58.5	50.0	187	1.23	11200	20171*
183	1100	1500	94.1	23353	23.3	219	364	44.9	23.6	44.0	57.6	50.5	137	1.37	11200	19527*
184	1100	1000	93.7	24821	23.7	263	367	48.3	24.8	44.7	58.2	53.1	210	1.37	11200	20024*
185	1100	500	90.4	26536	27.5	475	524	67.9	22.8	48.0	61.8	49.1	282	1.49	11200	23101*
2,000 RPM																
186	1100	2140	88.5	72717	136	429	845	26.1	41.6	59.7	76.6	86.3	312	1.34	11200	8985
187	1100	1500	89.4	78132	58.5	671	479	38.9	37.7	65.0	82.9	78.7	272	1.09	11200	10655

*Designs exceeded stress limit of rotor steel

3.1.4 Comparison of Weight and Efficiency as a Function of Generator Rating

Figure 3.1.4-1 illustrates the range of designs calculated and the practical design areas found from the calculations. Table 3.1.4-1 shows the parameters which produced the lightest weight, highest efficiency designs for each rating. Weight and efficiency vs. rating at various speeds, voltages, and coolant temperatures are discussed in the following sections.

Tables 3.1.4-2, 3, and 4, following each discussion, summarize the comparisons made.

3.1.4.1 Effect of Speed (Figures 3.1.4-2 through 3.1.4-13 and Table 3.1.4-2)

Weight

The weight vs. rating curves at various speeds show a 500°F coolant temperature to be the most suitable for comparison of the one to ten-megawatt ratings. Above 500°F only one and two-megawatt designs were found practical without decreasing the speed below 10,000 RPM.

At 10,000 RPM and 500°F coolant temperature, designs which did not exceed the stress limits of the rotor steel were obtained from one to ten megawatts. At 10,000 RPM and 800°F coolant temperature, only one and two-megawatt designs were found practical. Table 3.1.4-2 shows a lower weight to power ratio for the five-megawatt, 10,000 RPM, 500°F designs than for the other practical 10,000 RPM designs. From the table and curves, the 10,000 RPM designs are seen to be heavier than the designs at higher speeds.

DESIGN CALCULATIONS FOR PARAMETRIC STUDY

Notes: (1) Each design point shown was calculated at 500, 1000, 1500 & 2140 L-N Volts.

(2) o Designates practical design points calculated.

(3) Δ Designates calculated designs which exceeded rotor-steel stress limits.

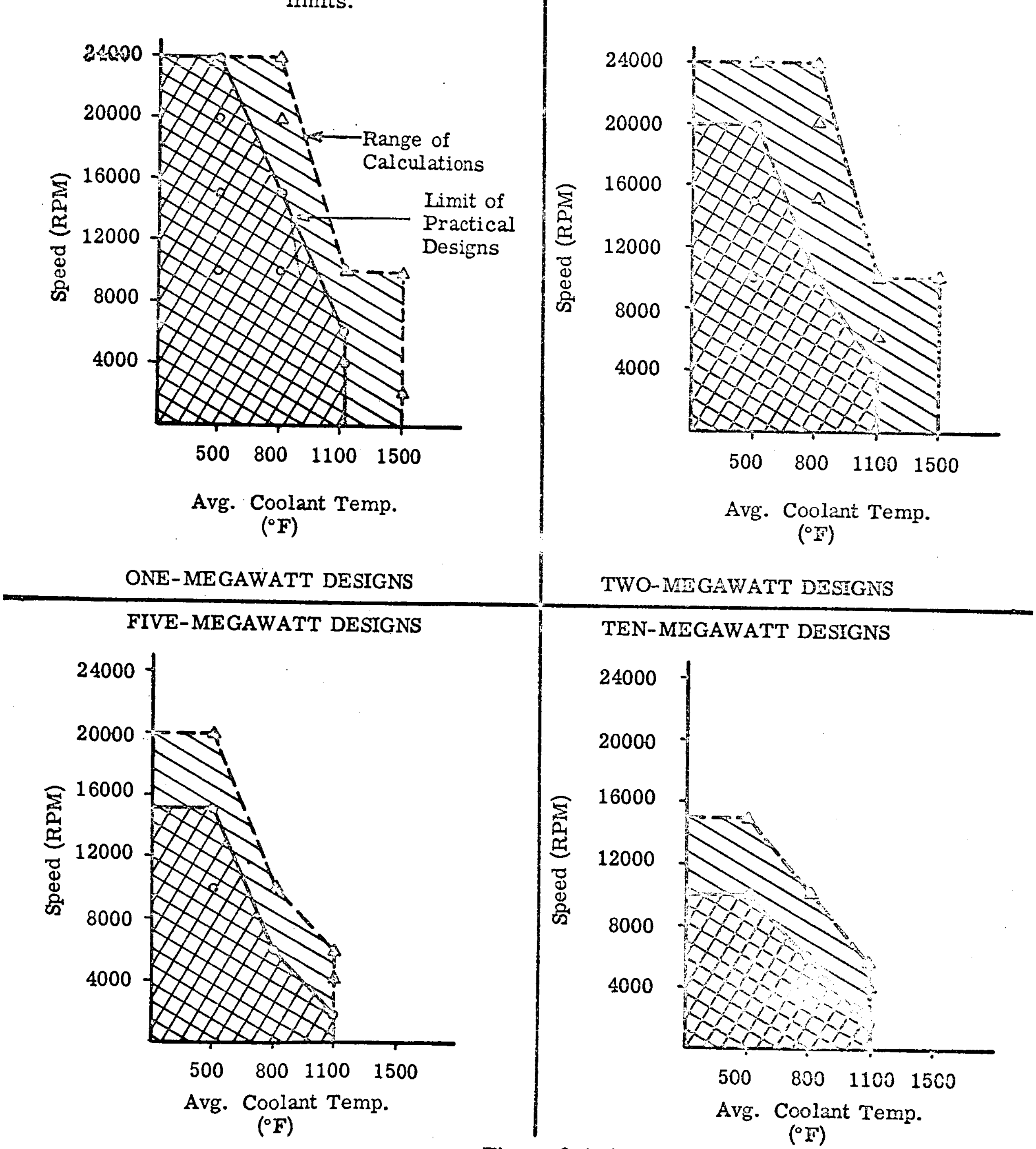


Figure 3.1.4-1

TABLE 3.1.4-1

RATING IN MEGAWATTS	LIGHTEST WT., HIGHEST EFFICIENCY DESIGNS CALCULATED					LBS/KW
1	500 V,	24,000 RPM,	500°F,	458 Lbs.	95.2% Eff.	.458
1	1500 V,	24,000 RPM,	500°F,	463 Lbs.	95.4% Eff.	.463
1	2140 V,	24,000 RPM,	500°F,	504 Lbs.	94.9% Eff.	.504
2	1000 V,	15,000 RPM,	500°F,	967 Lbs.	95.8% Eff.	.484
2	1500 V,	15,000 RPM,	500°F,	988 Lbs.	95.3% Eff.	.494
2	1000 V,	20,000 RPM,	500°F,	1009 Lbs.	95.6% Eff.	.505
5	1500 V,	15,000 RPM,	500°F,	2938 Lbs.	95.7% Eff.	.587
5	500 V,	15,000 RPM,	500°F,	3132 Lbs.	95.2% Eff.	.626
5	1000 V,	10,000 RPM,	500°F,	3338 Lbs.	95.8% Eff.	.668
5	500 V,	10,000 RPM,	500°F,	3392 Lbs.	95.3% Eff.	.678
10	500 V,	10,000 RPM,	500°F,	7039 Lbs.	91.1% Eff.	.704
10	1500 V,	10,000 RPM,	500°F,	7215 Lbs.	95.8% Eff.	.722
10	2140 V,	10,000 RPM,	500°F,	8503 Lbs.	95.7% Eff.	.850
10	1000 V,	10,000 RPM,	500°F,	8836 Lbs.	95.0% Eff.	.884

TABLE 3.1.4-2

Effect of Speed on Weight and Efficiency

MEGAWATTS	SPEED	AVG. COOLANT TEMPERATURE	LBS/KW*	AVG.* EFFICIENCY
1	24,000 RPM	500°F	.47	95.2%
1	20,000 RPM	500°F	.50	94.9%
2	20,000 RPM	500°F	.55	95.3%
1	15,000 RPM	500°F	.60	94.8%
2	15,000 RPM	500°F	.53	95.3%
5	15,000 RPM	500°F	.69	95.3%
1	15,000 RPM	800°F	.65	94.8%
1	10,000 RPM	500°F	.80	94.4%
2	10,000 RPM	500°F	.73	93.4%
5	10,000 RPM	500°F	.68	95.4%
10	10,000 RPM	500°F	.75	94.4%
1	10,000 RPM	800°F	.83	94.1%
2	10,000 RPM	800°F	.91	94.3%
5	6000 RPM	800°F	1.37	94.7%
10	6000 RPM	800°F	1.38	94.8%
1	6000 RPM	1100°F	1.58	92.6%
1	4000 RPM	1100°F	3.31	89.7%
2	4000 RPM	1100°F	2.75	91.6%

*Lbs/KW and average efficiencies were calculated using the average of the electrical weights of the efficiencies for the 500, 1000, 1500, and 2140 volt designs at each rating, speed, and coolant temperature shown.

A speed of 15,000 RPM, at a coolant temperature of 500°F, limited the maximum practical rating to five-megawatts. At 15,000 RPM, 800°F only one-megawatt designs were found practical. Of the practical 15,000 RPM designs, the two-megawatt, 500°F designs had the lowest weight to power ratios, as seen in Table 3.1.4-2.

A speed of 20,000 RPM, at a coolant temperature of 500°F, limited the maximum practical ratings to two-megawatts. No 20,000 RPM designs were found practical at coolant temperatures of 800°F and above. The one-megawatt, 20,000 RPM, 500°F designs had a lower weight to power ratio than the two-megawatt, 20,000 RPM, 500°F designs.

At 24,000 RPM, 500°F, only one-megawatt designs were found practical. 24,000 RPM designs at higher ratings or at higher temperatures exceeded the stress limits of the rotor steel. The one-megawatt, 24,000 RPM, 500°F designs had the lowest weight to power ratios of all designs calculated.

The rated speed was reduced to 6000 RPM, to obtain practical five and ten-megawatt designs at an average coolant temperature of 800°F and to obtain practical one-megawatt designs for an average coolant temperature of 1100°F. The five and ten-megawatt, 6000 RPM, 800°F designs showed approximately equal average ratios of weight to power, while the one-megawatt, 6000 RPM, 1100°F designs showed a higher weight-to-power ratio. The 6000 RPM designs had weight-to-power ratios of about 1.5 times higher than the 10,000 RPM designs.

The rated speed was reduced to 4000 RPM to obtain practical two-megawatt, 1100°F designs. The two-megawatt designs showed a weight-to-power advantage over the one-megawatt designs at this speed and temperature. The 4000 RPM designs had weight-to-power ratios in the order of three to four times higher than the 10,000 RPM designs.

Efficiency

The 10,000 RPM curves indicate the highest efficiencies can be obtained at a rating of five megawatts for this operating speed. Comparison of the tabulated data (for the 10,000 RPM 2, 5, and 10-megawatt designs) shows that the five-megawatt average iron loss is about 2.5 times that of the two-megawatt designs, while the five-megawatt average copper loss is about 35% greater than for the two-megawatt designs. Since total losses showed less than a proportional increase with rating in going from two to five megawatts, the five-megawatt designs show higher efficiencies. In going from five megawatts to ten megawatts the average iron loss increased in the order of 2.8 times while the average copper loss increased about 63%. Since total losses showed greater than a proportional increase in going from five to ten megawatts (because of the large increase in iron losses) the five-megawatt, 10,000 RPM designs in general show higher efficiencies.

The 15,000 RPM curves show higher efficiencies than the 10,000 RPM curves for all one and two-megawatt designs. The practical five-megawatt, 15,000 RPM designs showed, in general, efficiencies equal to or higher than the five-megawatt, 10,000 RPM designs. Since the number of five-megawatt designs at 15,000 RPM was limited by the allowable rotor-stress, the two-megawatt designs appear best in terms of efficiency at 15,000 RPM.

A speed of 20,000 RPM limited the maximum practical ratings to two megawatts. The practical 20,000 RPM, two-megawatt designs show efficiencies nearly equal to those of the 15,000 RPM, two-megawatt designs and in general higher than the efficiencies of the one-megawatt, 20,000 RPM designs.

At 24,000 RPM only one-megawatt ratings were found practical. The 24,000 RPM, one-megawatt designs in general, had higher efficiencies than one-megawatt designs at lower speeds.

The 6000 RPM, 800°F, five and ten-megawatt designs show approximately equal average efficiencies while the 4000 RPM, 1100°F designs show an efficiency advantage for the two-megawatt ratings over the one-megawatt ratings.

The best designs, at each speed in terms of average efficiency, of those calculated are:

PRACTICAL MEGAWATT RATINGS CALCULATED	DESIGNS WITH HIGHEST AVG. EFFICIENCIES
1	1 megawatt, 500°F at 24,000 RPM - 95.2% Avg.
1, 2	2 megawatts, 500°F at 20,000 RPM - 95.3% Avg.
1, 2, 5	2 & 5 megawatts, 500°F at 15,000 RPM - 95.3% Avg.
1, 2, 5, 10	5 megawatts, 500°F at 10,000 RPM - 95.4% Avg.
5, 10	10 megawatts, 800°F at 6000 RPM - 94.8% Avg.
1, 2	2 megawatts 1100°F at 4000 RPM - 91.6% Avg.

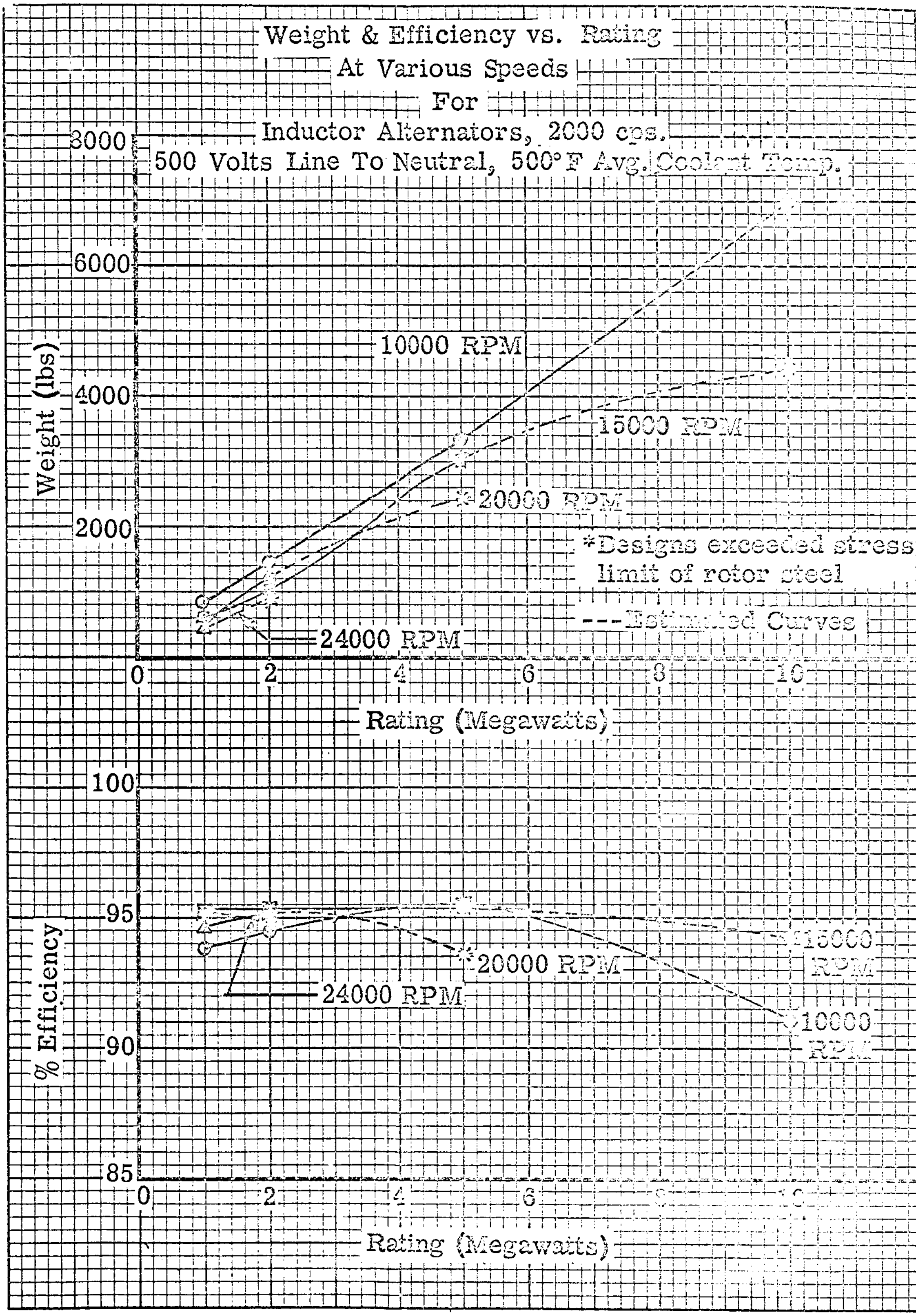
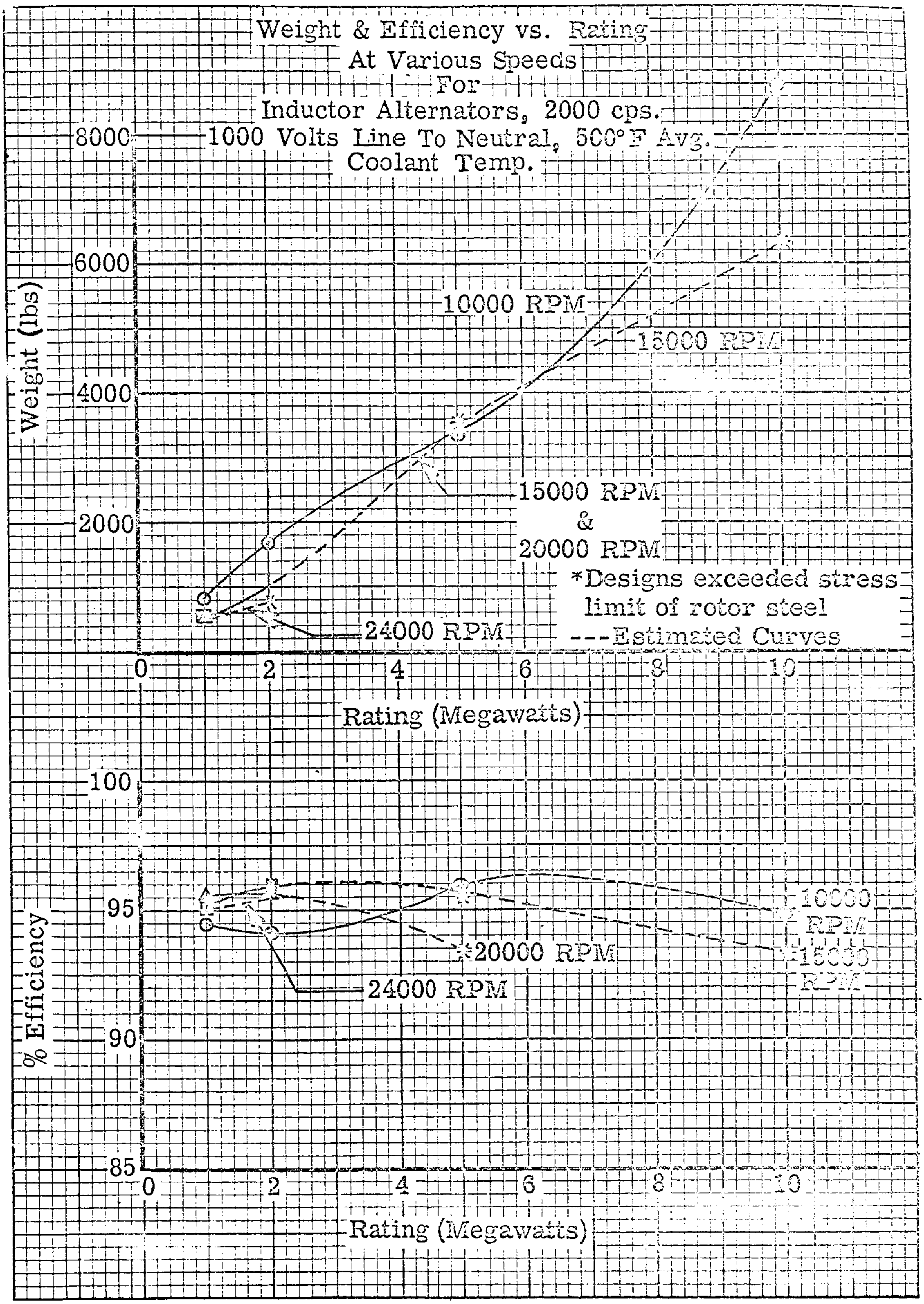
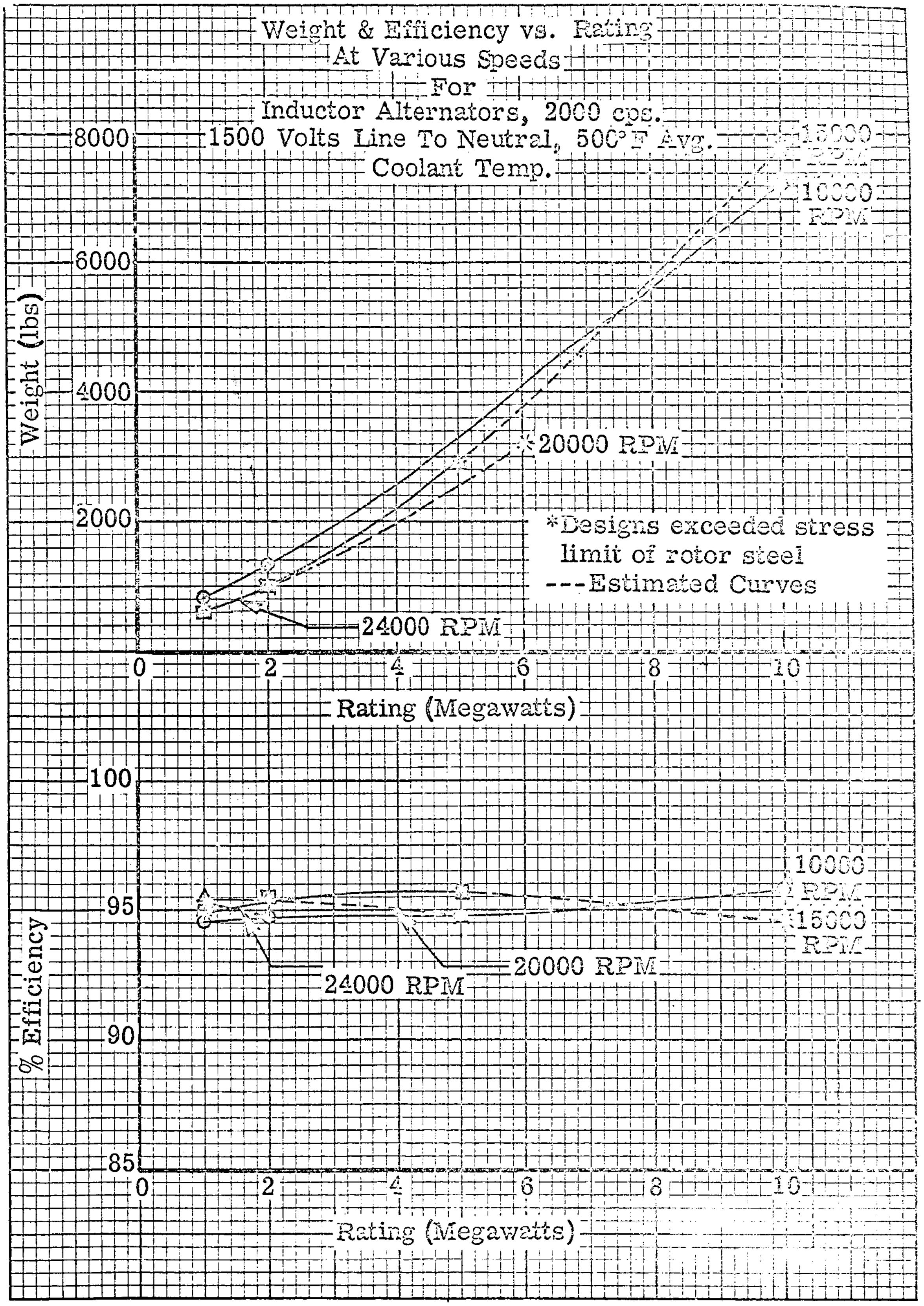

Weight & Efficiency vs. Rating
At Various Speeds
For
Inductor Alternators, 2000 cps.
500 Volts Line To Neutral, 500°F Avg. Coolant Temp.
Weight (lbs)
8000
6000
4000
2000
10000 RPM
15000 RPM
20000 RPM
24000 RPM
*Designs exceeded stress limit of rotor steel
---Estimated Curves
0
2
4
6
8
10
Rating (Megawatts)
% Efficiency
100
95
90
85
20000 RPM
24000 RPM
15000 RPM
10000 RPM
Rating (Megawatts)

Figure 3. 1. 4-2



Weight & Efficiency vs. Rating
At Various Speeds
For
Inductor Alternators, 2000 cps.
1000 Volts Line To Neutral, 500°F Avg.
Coolant Temp.
Weight (lbs)
8000
6000
4000
2000
10000 RPM
15000 RPM
15000 RPM
&
20000 RPM
24000 RPM
*Designs exceeded stress limit of rotor steel
---Estimated Curves
0
2
4
6
8
10
Rating (Megawatts)
% Efficiency
100
95
90
85
10000 RPM
*20000 RPM
15000 RPM
24000 RPM
0
2
4
6
8
10
Rating (Megawatts)

Figure 3.1.4-3



Weight & Efficiency vs. Rating
At Various Speeds
For
Inductor Alternators, 2000 cps.
1500 Volts Line To Neutral, 500°F Avg.
Coolant Temp.
Weight (lbs)
8000
6000
4000
2000
15000 RPM
10000 RPM
20000 RPM
*Designs exceeded stress limit of rotor steel
---Estimated Curves
24000 RPM
0
2
4
6
8
10
Rating (Megawatts)
% Efficiency
100
95
90
85
10000 RPM
15000 RPM
20000 RPM
24000 RPM
Rating (Megawatts)

Figure 3.1.4-4

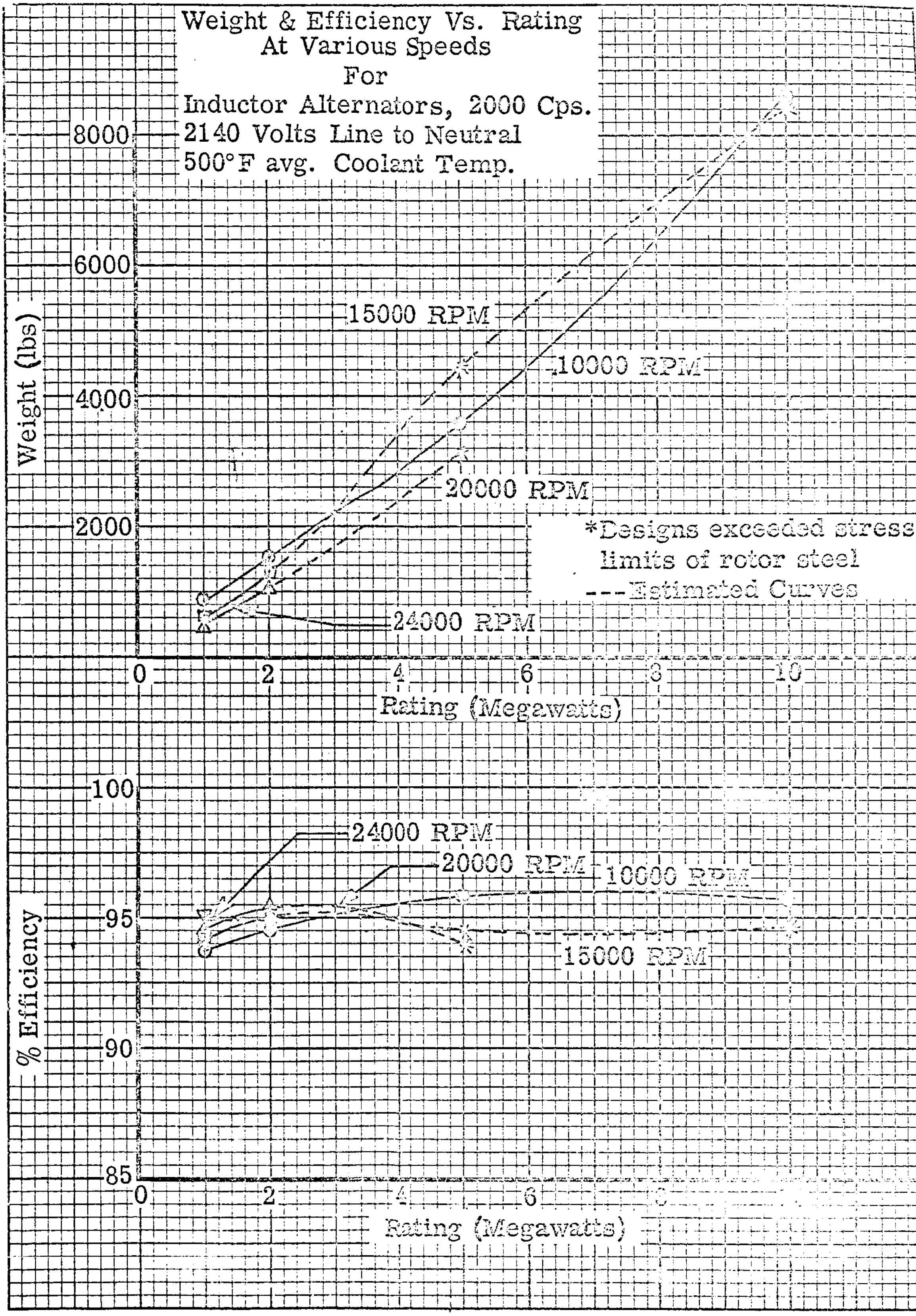
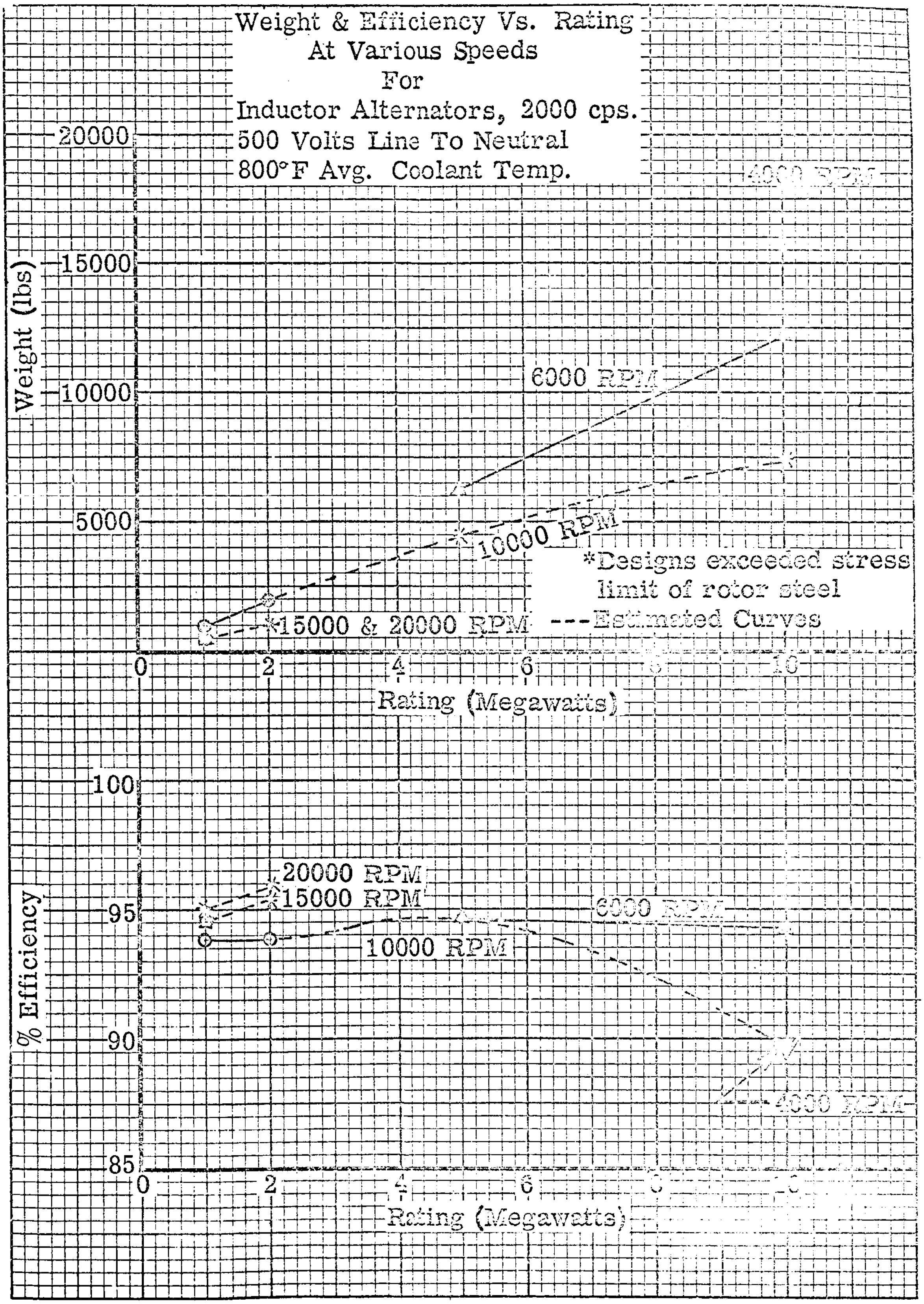

Weight & Efficiency Vs. Rating
At Various Speeds
For
Inductor Alternators, 2000 Cps.
2140 Volts Line to Neutral
500°F avg. Coolant Temp.
8000
6000
4000
2000
Weight (lbs)
15000 RPM
10000 RPM
20000 RPM
24000 RPM
*Designs exceeded stress limits of rotor steel
---Estimated Curves
0
2
4
6
8
10
Rating (Megawatts)
100
95
90
85
% Efficiency
24000 RPM
20000 RPM
10000 RPM
15000 RPM
0
2
4
6
Rating (Megawatts)

Figure 3.1.4-5



Weight & Efficiency Vs. Rating
At Various Speeds
For
Inductor Alternators, 2000 cps.
500 Volts Line To Neutral
800°F Avg. Coolant Temp.
Weight (lbs)
20000
15000
10000
5000
6000 RPM
10000 RPM
15000 & 20000 RPM
*Designs exceeded stress limit of rotor steel
---Estimated Curves
0
2
4
6
Rating (Megawatts)
% Efficiency
100
95
90
85
20000 RPM
15000 RPM
10000 RPM
Rating (Megawatts)

Figure 3.1.4-6

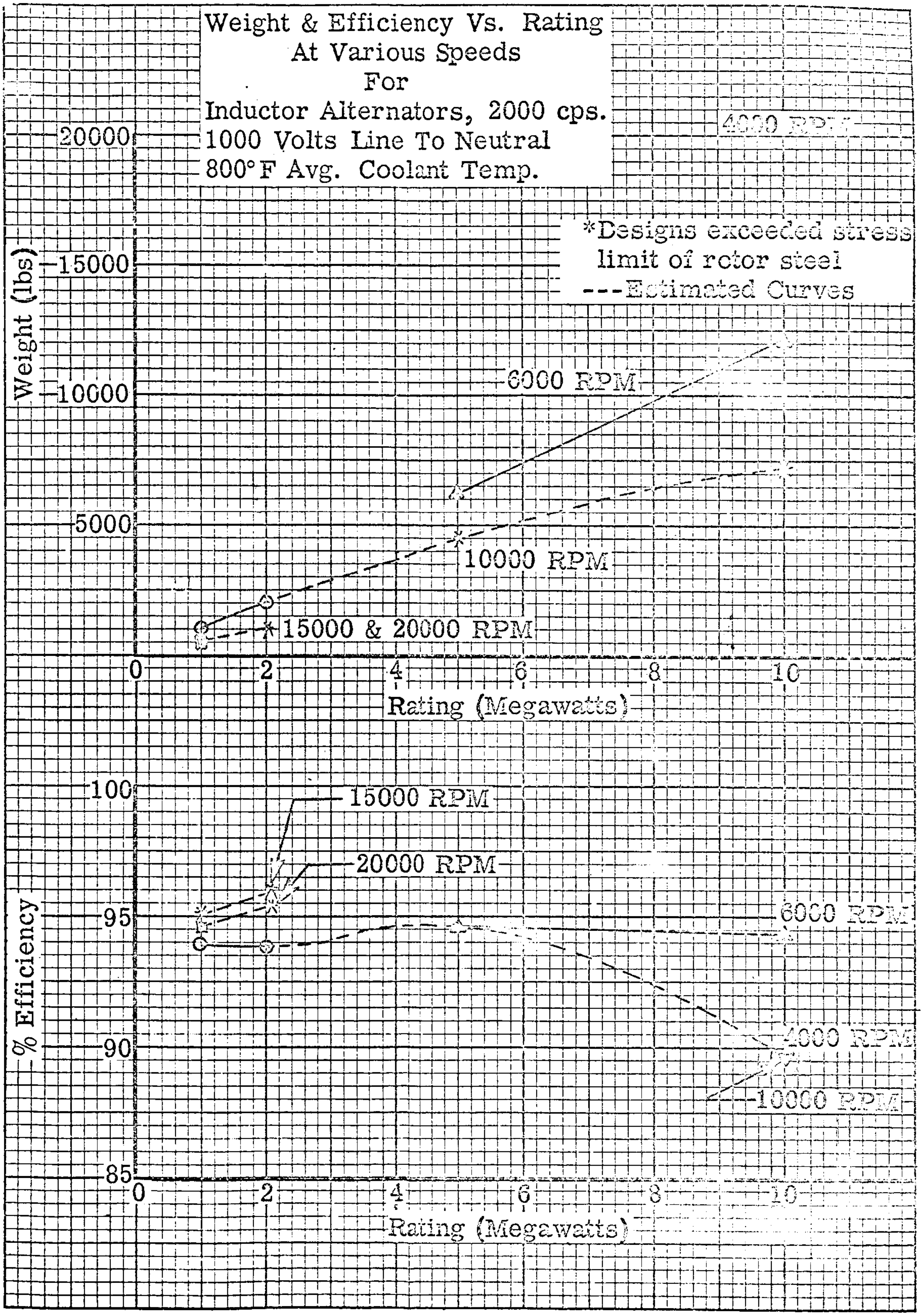
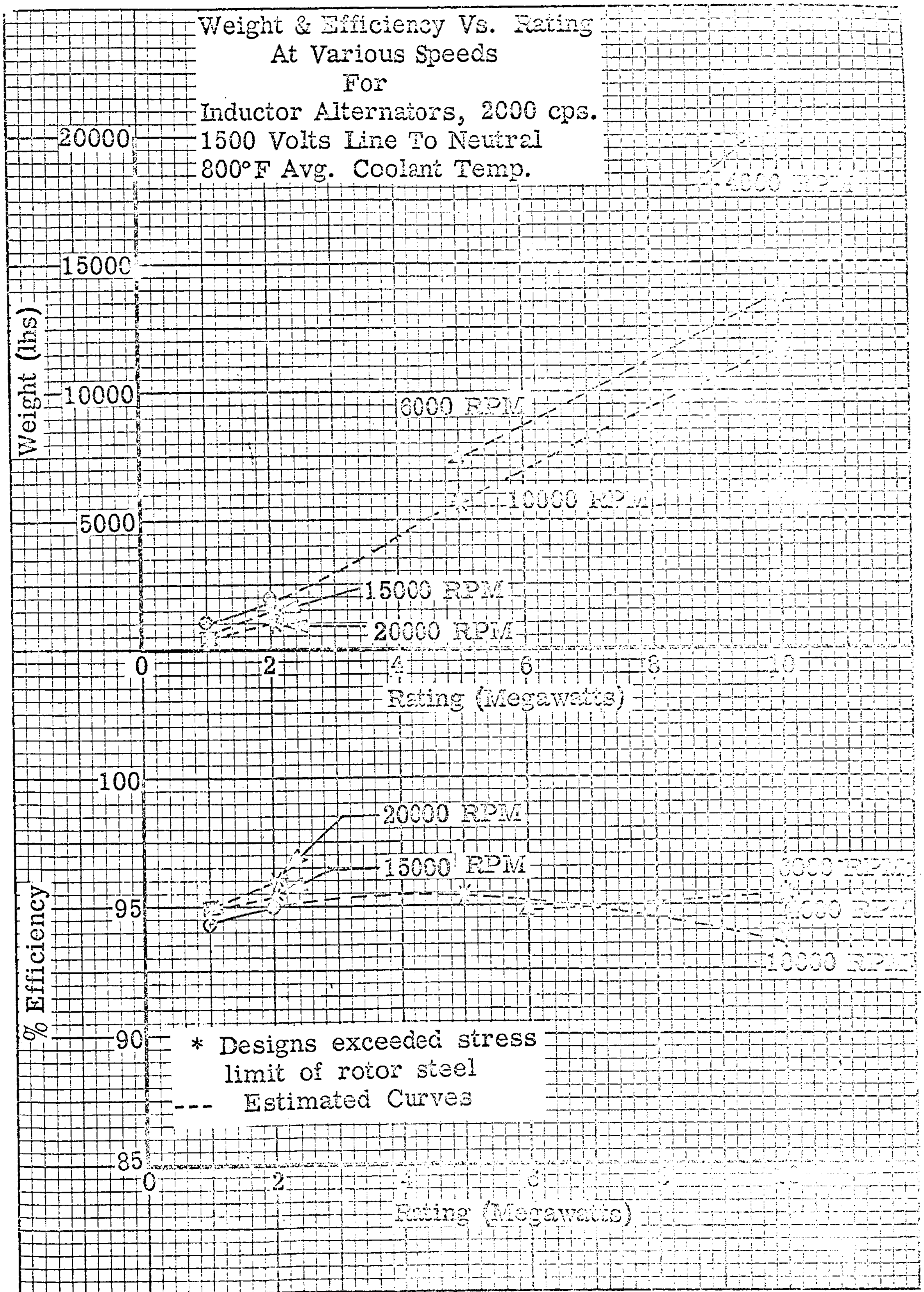

Weight & Efficiency Vs. Rating
At Various Speeds
For
Inductor Alternators, 2000 cps.
1000 Volts Line To Neutral
800°F Avg. Coolant Temp.
*Designs exceeded stress limit of rotor steel
---Estimated Curves
Weight (lbs)
20000
15000
10000
5000
4000 RPM
6000 RPM
10000 RPM
15000 & 20000 RPM
0
2
4
6
8
10
Rating (Megawatts)
% Efficiency
100
95
90
85
15000 RPM
20000 RPM
6000 RPM
4000 RPM
10000 RPM
0
2
4
6
8
10
Rating (Megawatts)

Figure 3. 1. 4-7



Weight & Efficiency Vs. Rating
At Various Speeds
For
Inductor Alternators, 2000 cps.
1500 Volts Line To Neutral
800°F Avg. Coolant Temp.
20000
15000
10000
5000
Weight (lbs)
4000 RPM
6000 RPM
10000 RPM
15000 RPM
20000 RPM
0
2
4
6
8
10
Rating (Megawatts)
100
95
90
85
% Efficiency
20000 RPM
15000 RPM
6000 RPM
4000 RPM
10000 RPM
* Designs exceeded stress limit of rotor steel
--- Estimated Curves
0
2
4
6
Rating (Megawatts)

Figure 3. 1. 4-8

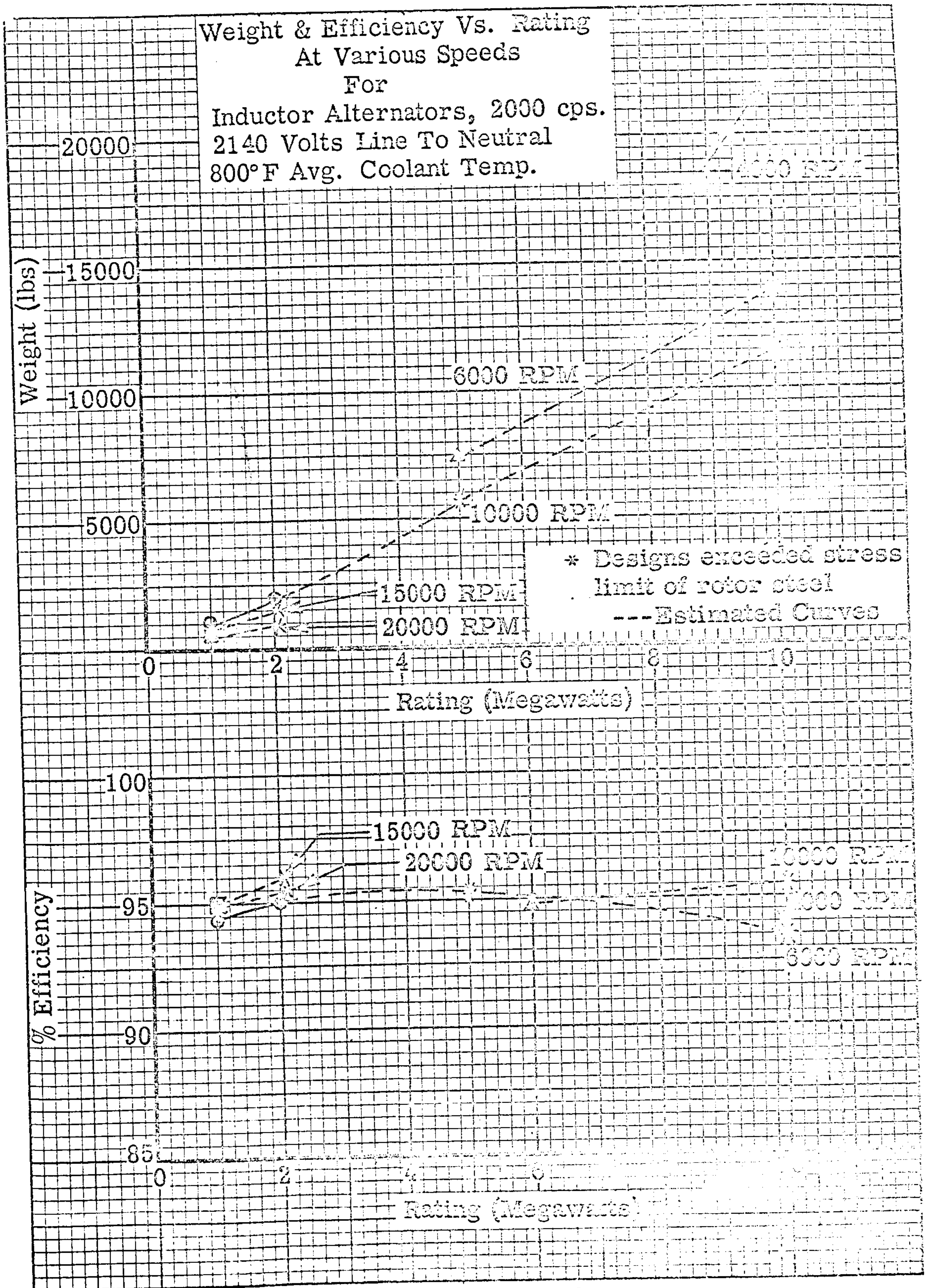

Weight & Efficiency Vs. Rating
At Various Speeds
For
Inductor Alternators, 2000 cps.
2140 Volts Line To Neutral
800°F Avg. Coolant Temp.
Weight (lbs)
20000
15000
10000
5000
0
2
4
6
8
10
4000 RPM
6000 RPM
10000 RPM
15000 RPM
20000 RPM
* Designs exceeded stress limit of rotor steel
---Estimated Curves
Rating (Megawatts)
% Efficiency
100
95
90
85
15000 RPM
20000 RPM
10000 RPM
6000 RPM
Rating (Megawatts)

Figure 3.1.4-9

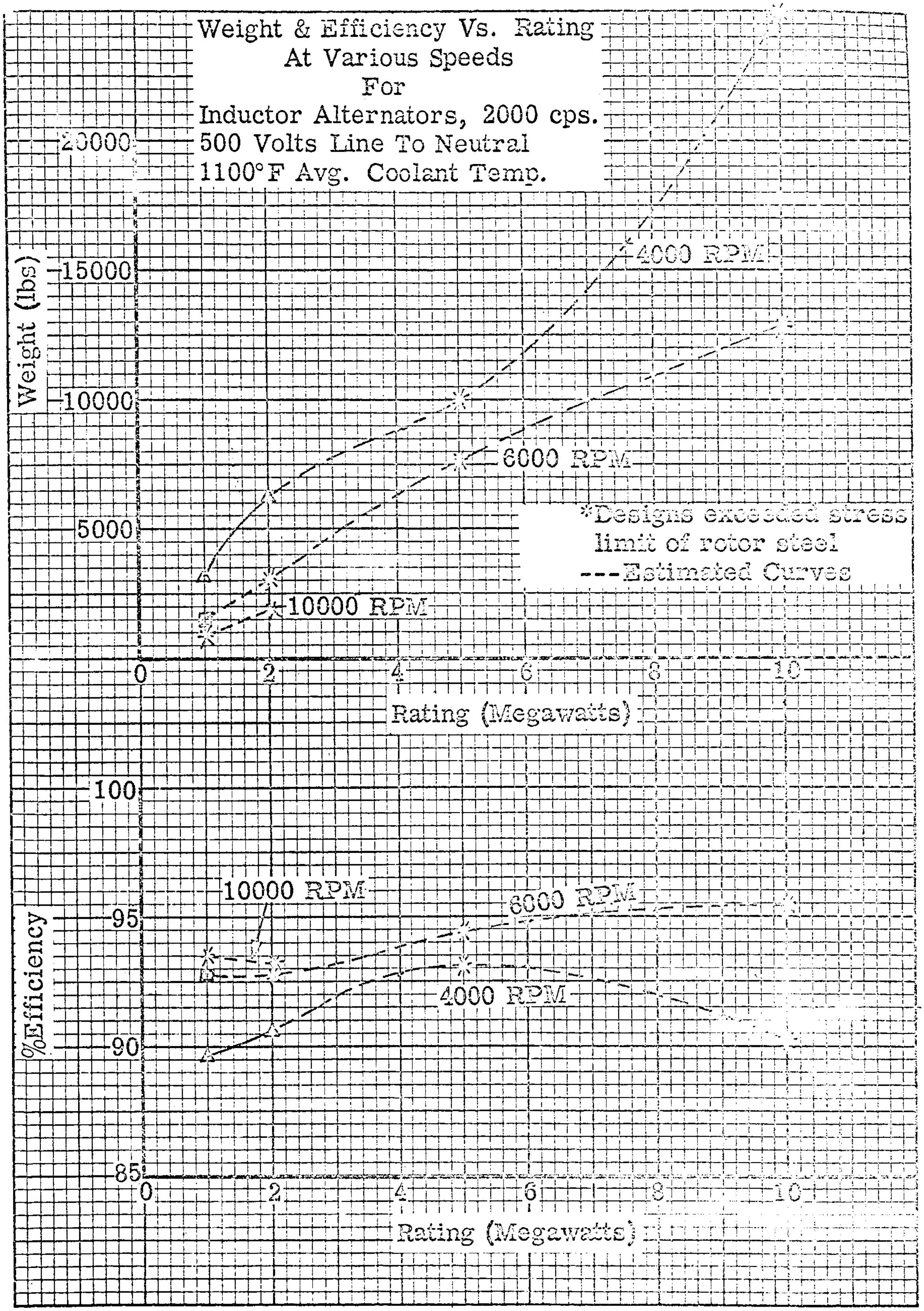


Figure 3. 1. 4-10

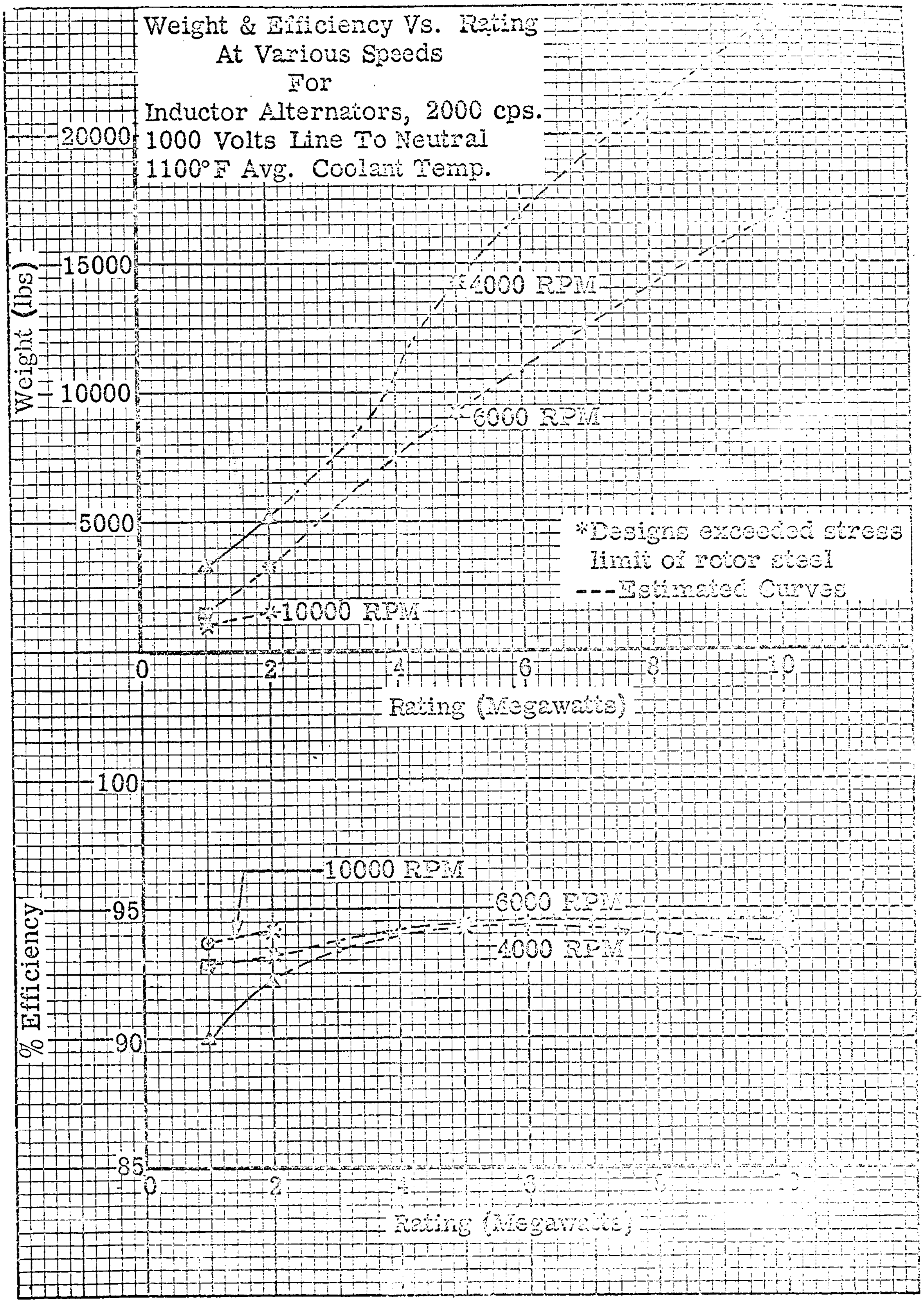


Figure 3. 1. 4-11

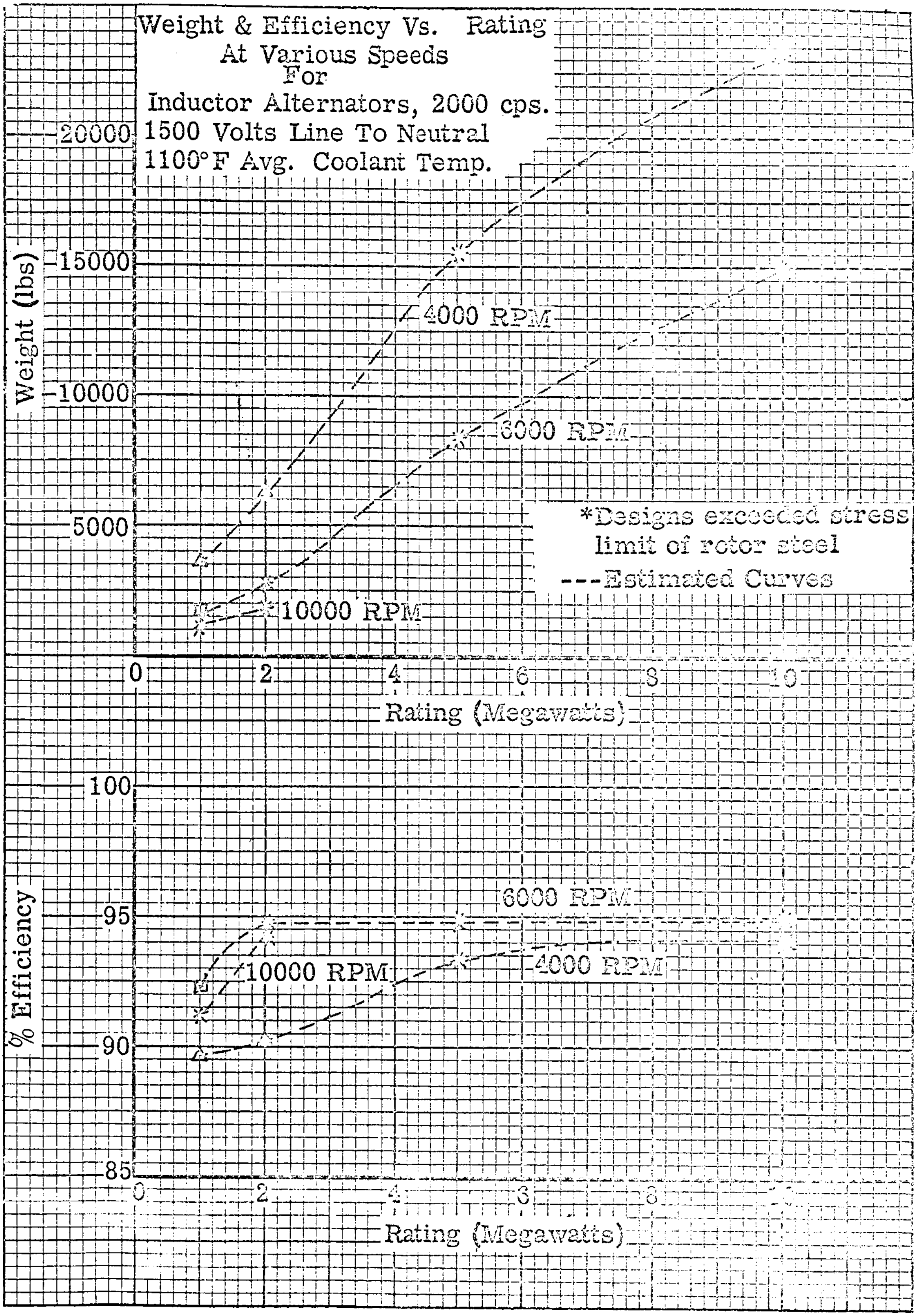


Figure 3. 1. 4-12

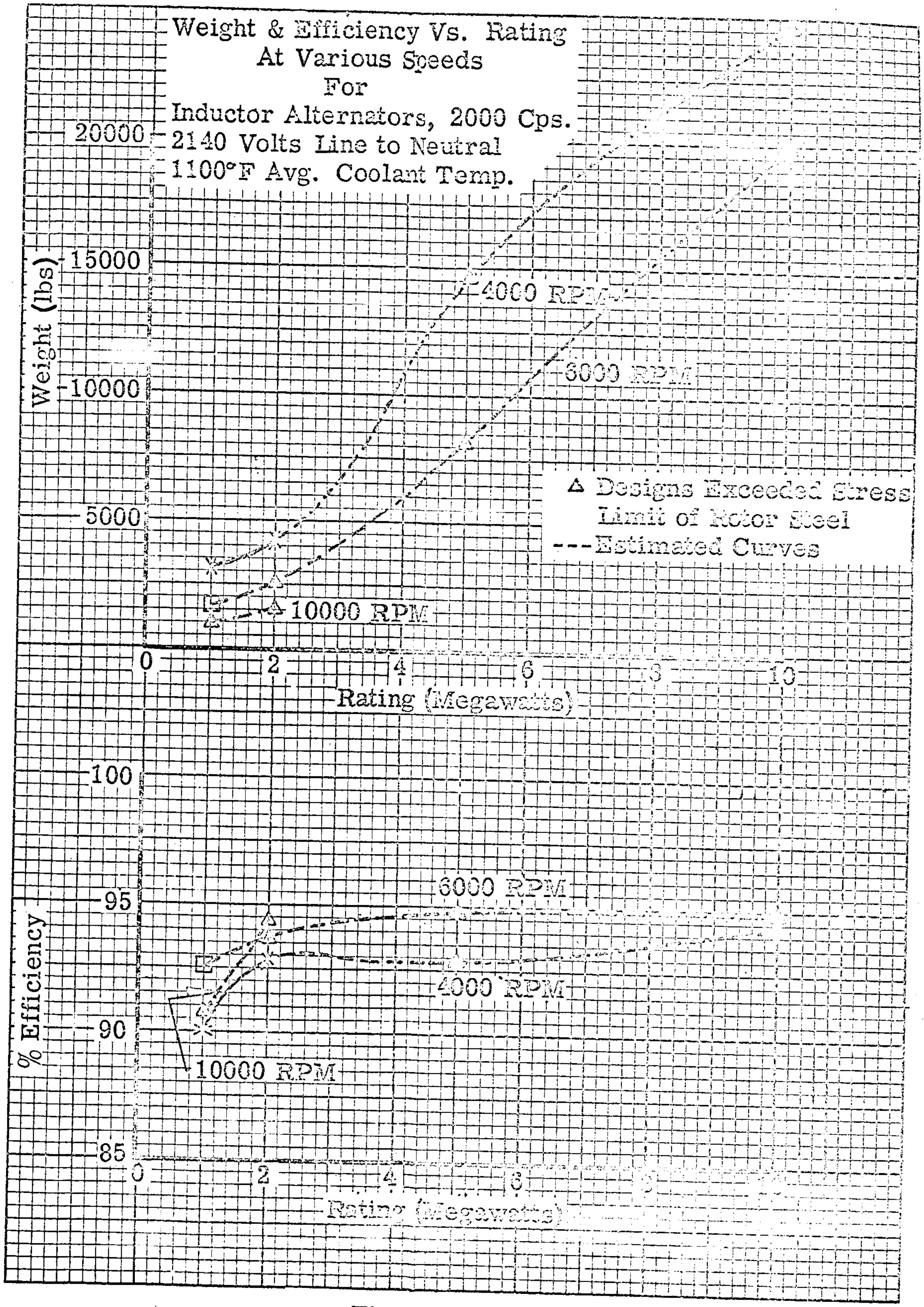


Figure 3.1.4-13

3.1.4.2 Effect of Voltage (Figures 3.1.4-14 through 3.1.4-20, Table 3.1.4-3)

Weight

The power-to-weight ratios and the efficiencies at each combination of speed, temperature, and rating show no definite changes in relative weight and efficiency ranking when designs at 500, 1000, 1500, and 2140 volts are compared; i.e. the best combination of parameters at one voltage shows the same relative advantages at the other voltages considered. For this reason, the best voltage range for each set of operating conditions will be discussed. Voltages are generator line-to-neutral voltages.

At a speed of 10,000 RPM and an average coolant temperature of 500°F (Figure 3.1.4-14), designs under five-megawatts show little difference in weight at the four generator voltages considered. At ten megawatts, the 1000 and 2140 volt designs show an increase in weight over the 500 and 1500 volt designs, because of the better combination of design parameters at the given operating conditions. Table 3.1.4-3 shows no marked tendency toward a single voltage producing the lightest weight 10,000 RPM designs. Three of the six lightest weight 10,000 RPM designs were at 500 volts and two were at 1000 volts. The lightest weight two-megawatt, 10,000 RPM design was at 1500 volts, but the second lightest two-megawatt, 10,000 RPM design at 500 volts was only about 4% heavier than the 1500 volt design. Based on these data, voltages of 500 to 1000 volts appear best weight-wise for 10,000 RPM designs for both 500°F and 800°F coolant temperatures.

At 15,000 RPM, 500°F, a somewhat more pronounced effect of generator voltage on weight is seen from Figure 3.1.4-16. From a weight standpoint,

TABLE 3.1.4-3

Effect of Voltage on Weight and Efficiency

SPEED	AVG. COOLANT TEMP.	RATING IN MEGA-WATTS	500 V		1000 V		1500 V		2140 V	
			LBS/KW	EFF.	LBS/KW	EFF.	LBS/KW	EFF.	LBS/KW	EFF.
24,000	500	1	.458	95.2	.458	95.1	.463	95.4	.504	94.9
20,000	500	1	.454	94.7	.485	95.4	.515	95.1	.534	94.4
20,000	500	2	.604	95.2	.505	95.6	.520	95.4	.563	95.2
15,000	500	1	.616	95.2	.564	95.1	.585	94.8	.605	93.9
15,000	500	2	.519	95.2	.484	95.8	.494	95.3	.630	95.0
15,000	500	5	.626	95.2	.687	95.6	.588	95.7	.888	94.5
15,000	800	1	.649	94.9	.662	95.1	.672	94.9	.627	94.1
10,000	500	1	.801	93.9	.018	94.4	.818	94.5	.861	93.6
10,000	500	2	.712	94.4	.812	94.0	.687	94.7	.723	94.5
10,000	500	5	.678	95.3	.667	95.8	1.30	94.8	.703	95.8
10,000	500	10	.704	91.1	.884	95.0	.722	95.8	.850	95.7
10,000	800	1	.802	93.9	.820	94.3	.820	94.3	.863	93.7
10,000	800	2	.915	93.8	.887	94.6	.936	95.0	.913	93.6

______ Lowest Lbs/KW

══════ Highest Efficiency

TABLE 3.1.4-3 (Cont'd)

Effect of Voltage on Weight and Efficiency

SPEED	AVG. COOLANT TEMP.	RATING IN MEGA-WATTS	500 V		1000 V		1500 V		2140 V	
			LBS/KW	EFF.	LBS/KW	EFF.	LBS/KW	EFF.	LBS/KW	EFF.
6000	800	5	1.24	94.6	1.33	94.3	1.49	94.9	1.44	95.1
6000	800	10	1.22	94.3	1.58	94.8	1.37	95.3	1.33	94.6
6000	1100	1	1.51	92.8	1.51	92.8	1.61	92.2	1.68	92.4
4000	800	10	2.05	89.6	2.25	94.0	2.05	93.7	2.22	94.9
4000	1100	1	3.24	89.6	3.26	89.3	3.66	89.7	3.09	90.0
4000	1100	2	3.21	90.6	2.58	92.4	3.12	90.2	2.10	93.0

_______ Lowest Lbs/KW

_______ Highest Efficiency

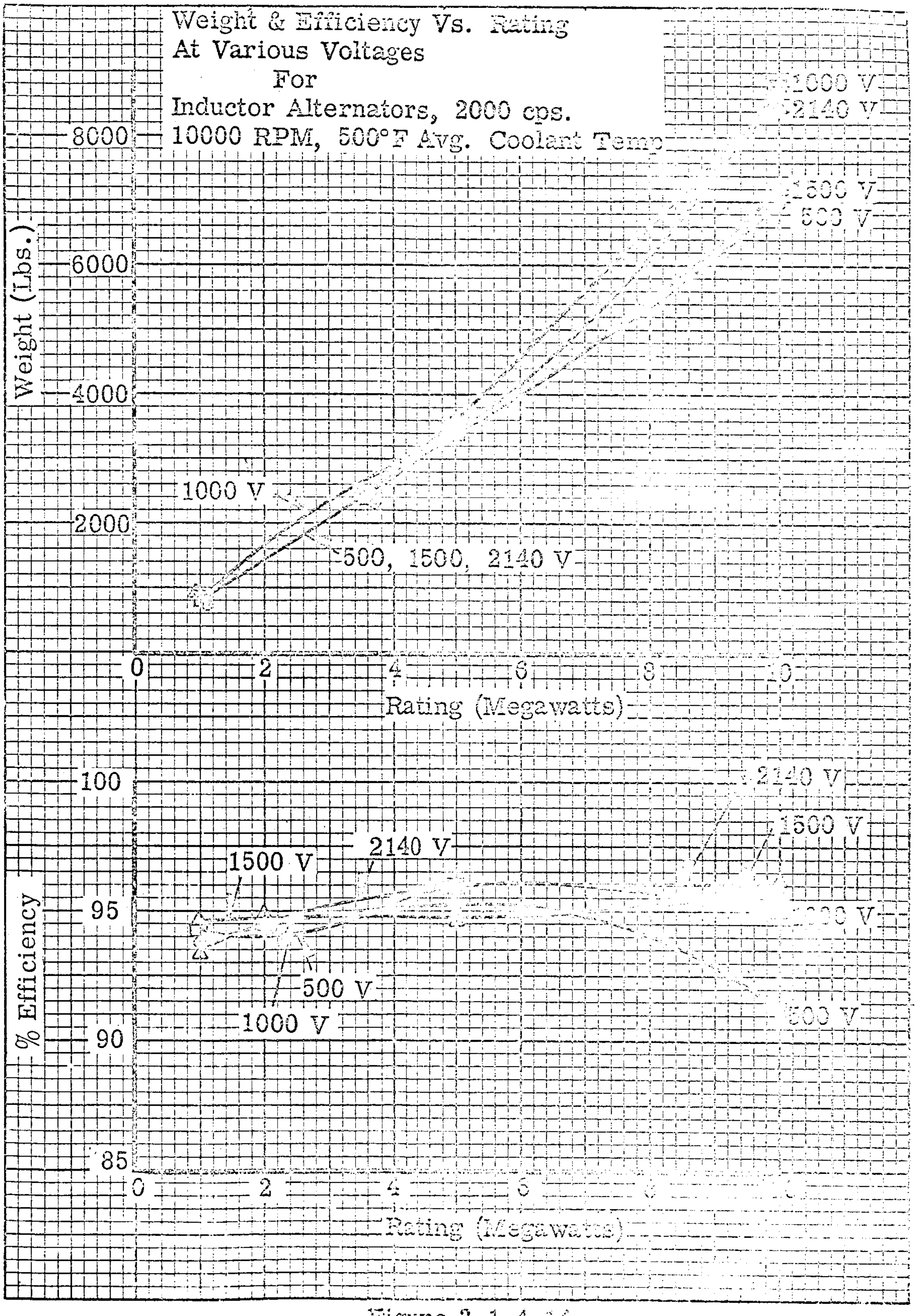


Figure 3.1.4-14

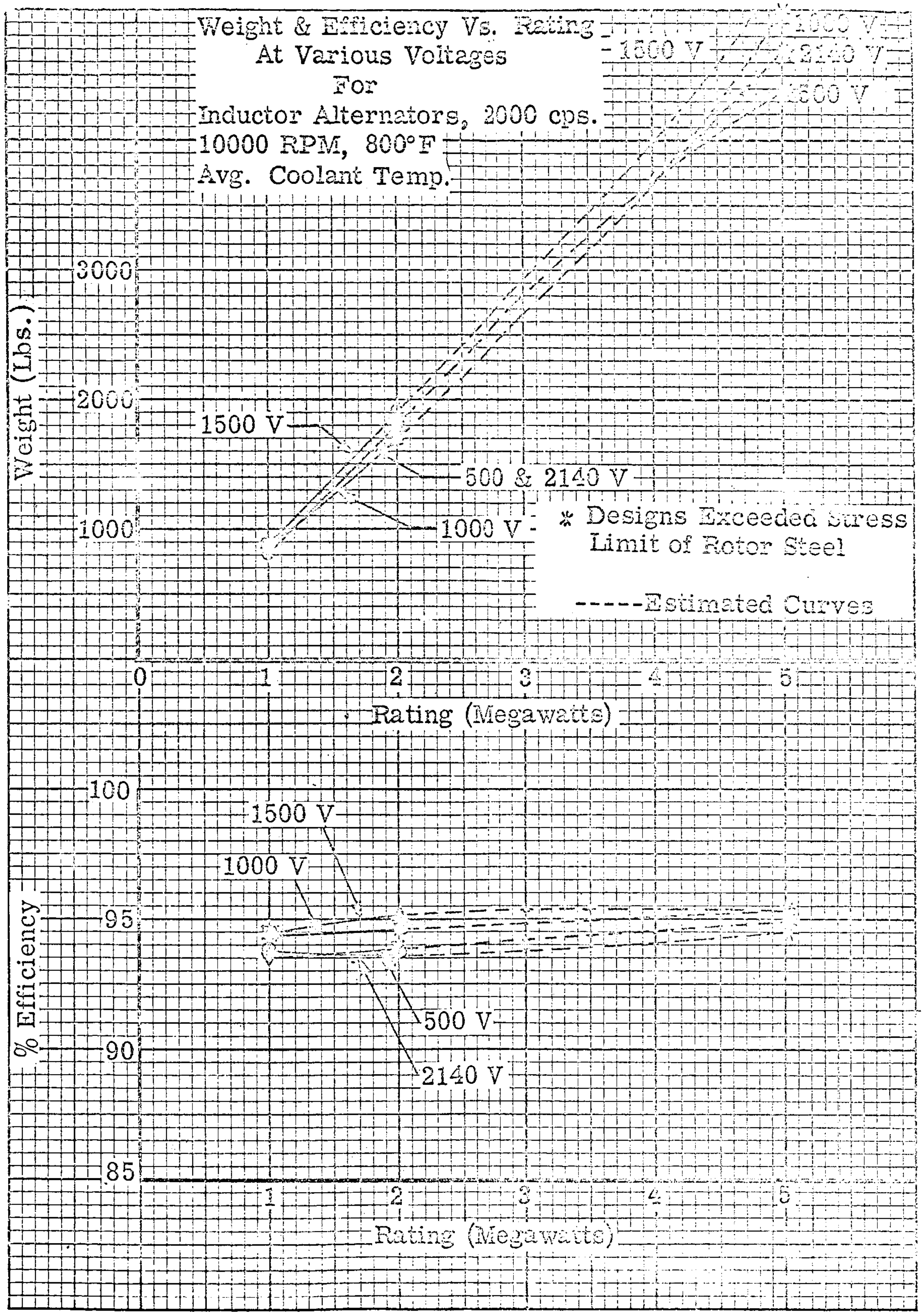


Figure 3.1.4-15

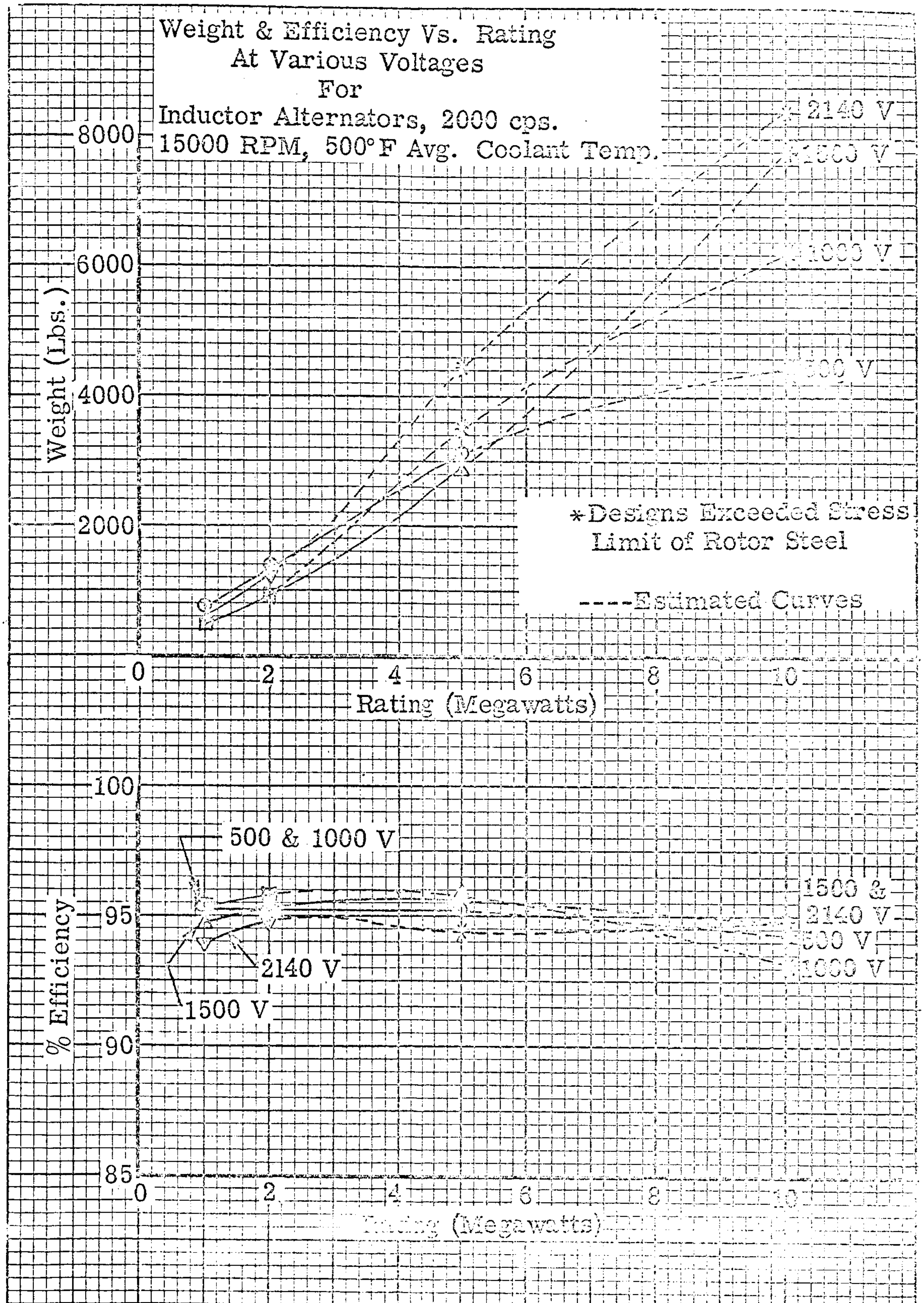


Figure 3.1.4-16

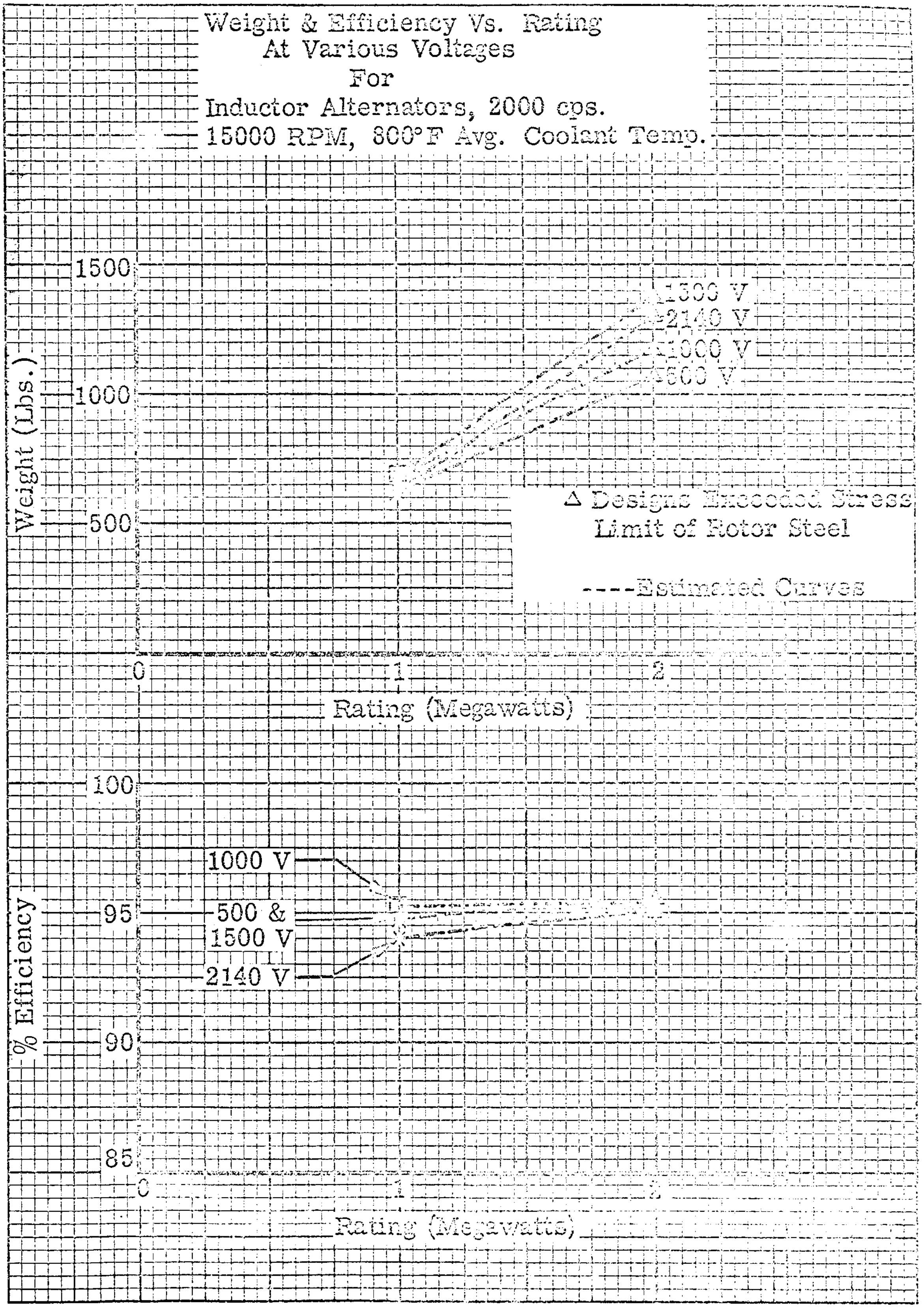


Figure 3.1.4-17

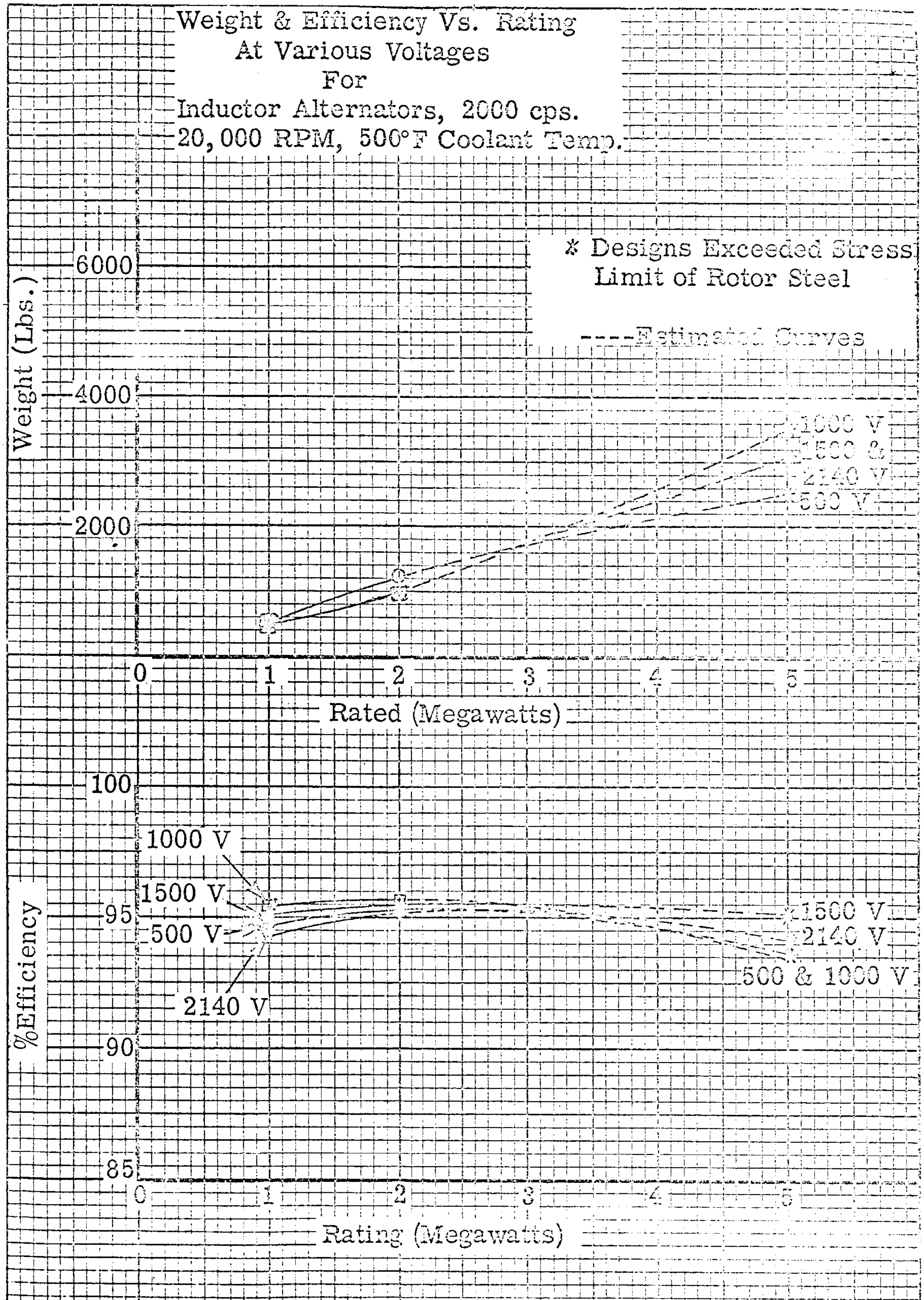


Figure 3.1.4-18

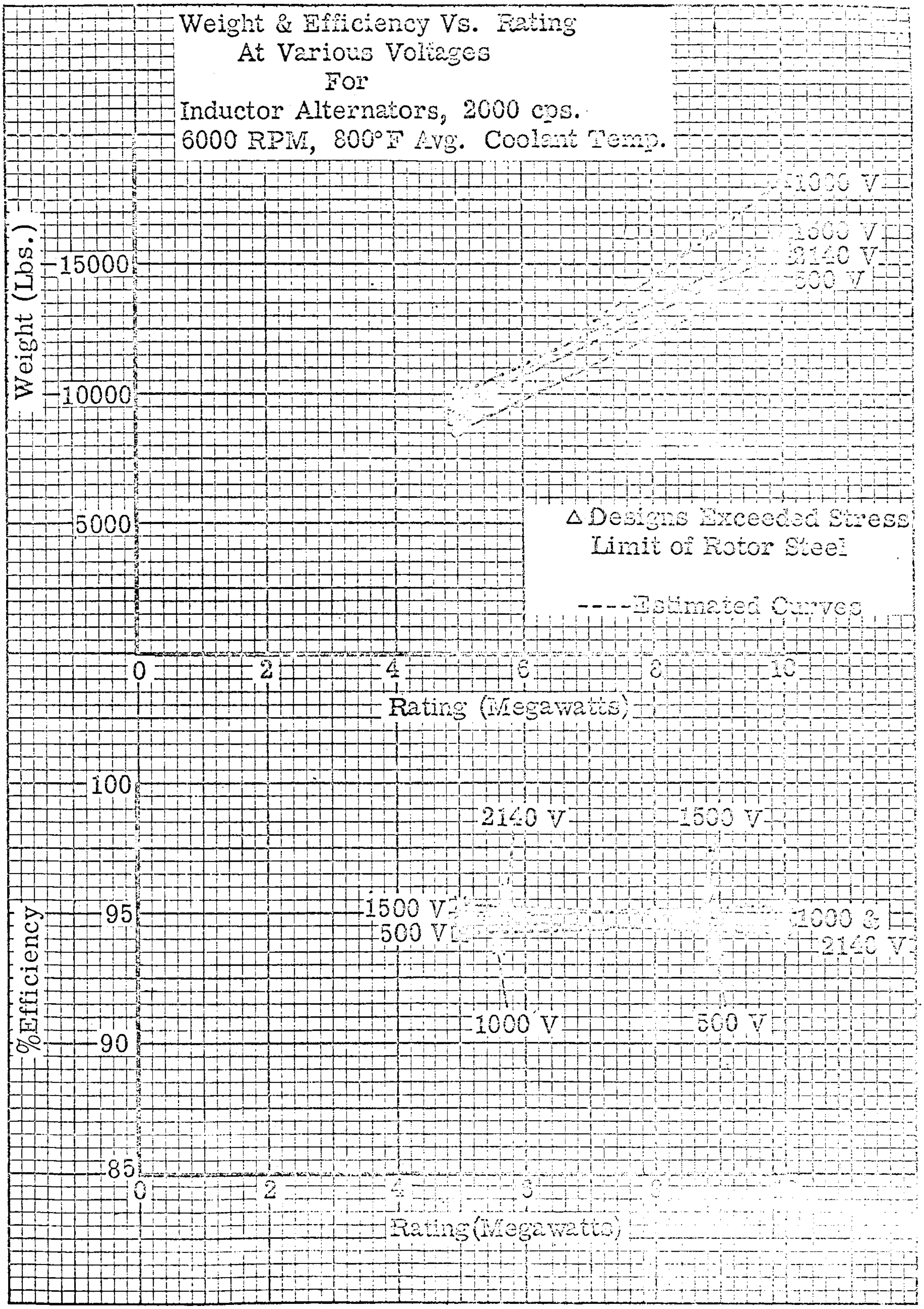


Figure 3.1.4-19

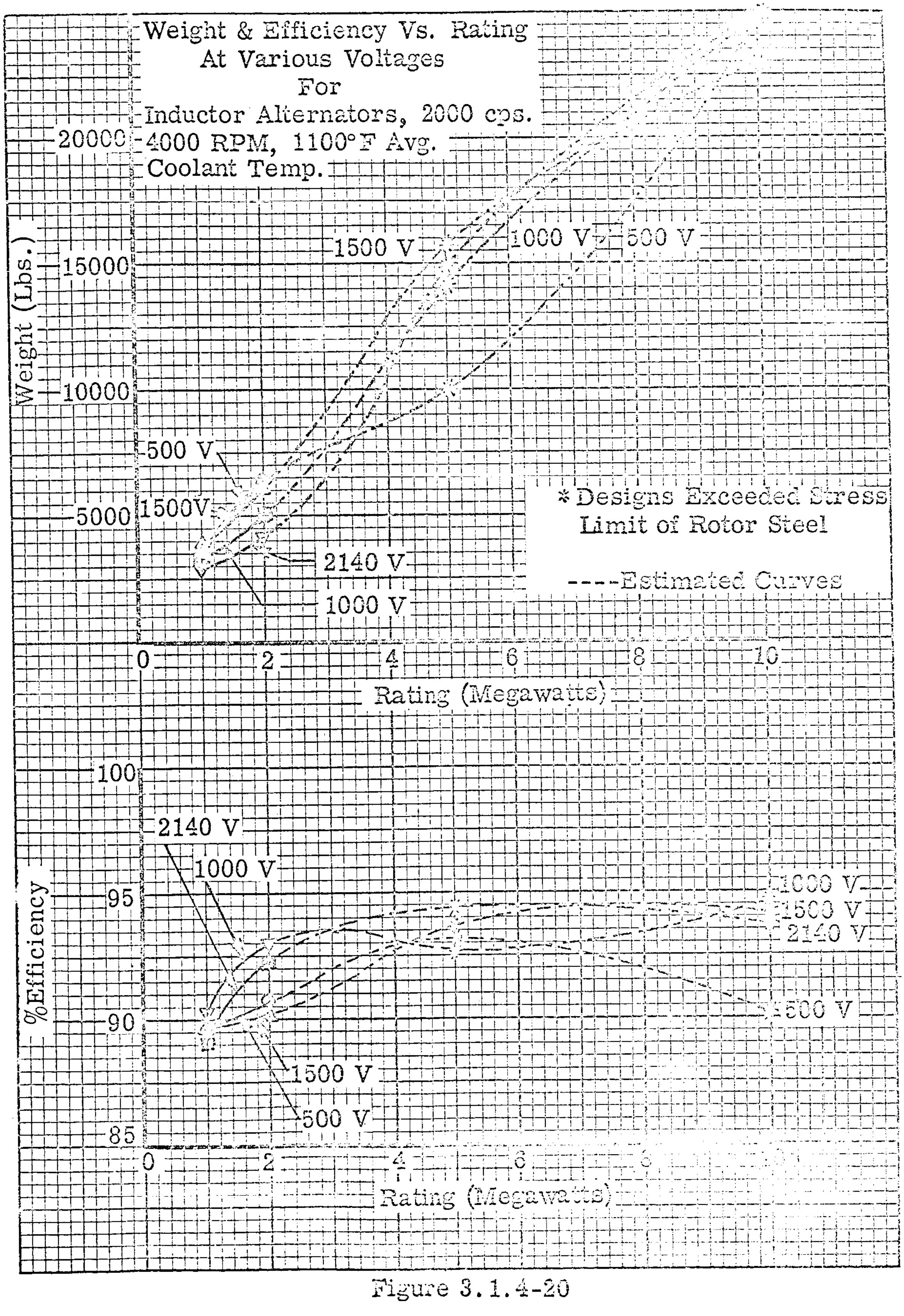


Figure 3.1.4-20

the best voltage for one and two-megawatt designs appears to be 1000 volts. At five-megawatts, 1500 volts shows a weight advantage. At 15,000 RPM, 800°F, only one-megawatt designs were found practical, and the effect of varying the voltage for those designs was found to be small. Based on the designs calculated, voltages of 1000 to 1500 volts appear, in general, to show the most weight advantage for 15,000 RPM designs.

At 20,000 RPM, 500°F, 500 volts produced the lightest weight one-megawatt design and 1000 volts produced the lightest weight two-megawatt design. Designs at higher ratings exceeded the stress limits of the rotor steel. The 500 to 1000 volt range appears best for 20,000 RPM designs, as well as for 24,000 RPM designs, as shown in Table 3.1.4-3.

At 6000 RPM, 800°F, a generator voltage of 500 volts produced the lightest weight five and ten-megawatt designs. At 6000 RPM, 1100°F, a voltage of 500 volts again produced the lightest weight one-megawatt design. Based on the limited number of practical 6000 RPM designs calculated, 500 volts appears best in terms of weight.

At 4000 RPM, 800°F, voltages of 500 and 1500 volts resulted in the lightest weight ten-megawatt designs. At 4000 RPM, 1100°F, a voltage of 2140 volts produced the lightest weight one and two-megawatt designs. Based on the limited number of practical 4000 RPM designs calculated, generator voltages from 1500 to 2140 volts appear to result in the largest weight advantage.

Efficiency

At 10,000 RPM, 500°F, the highest one and two-megawatt generator efficiencies occurred at 1500 volts, the highers five-megawatt efficiencies occurred at 1000 and 2140 volts, and the highest ten-megawatt efficiencies occurred at 1500 volts. It is reasonable to assume that the 1500 volt, five-megawatt design could be improved to increase the efficiency by 1%, because five-megawatt designs at higher and lower voltages had 1% higher efficiencies and all 10,000 RPM designs at other ratings had their highest efficiencies at 1500 volts. Based on the majority of designs calculated, a generator voltage of 1500 volts appears to produce the highest generator efficiencies for operation at 10,000 RPM.

At 15,000 RPM, figures 3.1.4-16 and 17, show that the practical one and two megawatt designs have the highest efficiencies at 500 to 1000 volts. The five-megawatt, 500°F, 15,000 RPM design has highest efficiency at 1500 volts, however, its efficiency at 1000 volts is only lower by 1%. Likewise, the efficiency of the one-megawatt, 500°F, 15,000 RPM is only .1% lower at 1000 volts compared to 500 volts. From the designs calculated, 1000 volts appears to give the highest efficiencies for 15,000 RPM designs.

At 20,000 RPM, the practical one and two megawatt designs had the highest efficiency at 1000 volts and at 24,000 RPM the practical one-megawatt designs had the highest efficiency at 1500 volts. These designs, in addition to the designs previously discussed, further indicate that the highest efficiencies can be obtained at generator voltages of 1000 to 1500 volts over a speed range of 10,000 to 24,000 RPM.

The 6000 RPM curves and Table 3.1.4-3 indicate a five-megawatt generator voltage of 2140 volts for the highest efficiency design with 1500 volts producing an efficiency lower by only .2%. A ten-megawatt-generator voltage of 1500 volts at 6000 RPM resulted in the highest efficiency design. Voltages of 500 and 1000 produced the highest efficiency one-megawatt, 1100°F design at 6000 RPM.

The 4000 RPM curves indicate that a voltage of 2140 volts results in the highest efficiencies for the one and two-megawatt, 1100°F designs and for the ten-megawatt, 800°F designs.

3.1.4.3 Effect of Coolant Temperature (Figures 3.1.4-21 through 3.1.4-40, Table 3.1.4-4)

Weight and Efficiency

These curves again illustrate the limited number of practical designs which did not exceed the rotor-steel stress limits over the 500°F to 1500°F coolant-temperature range. In general, the lowest weight, highest efficiency designs were obtained at 500°F.

The 10,000 RPM curves, figures 3.1.4-21 to 3.1.4-24 show a definite weight advantage for a 500°F coolant temperature for generator ratings above one megawatt. The effects of an increase in coolant temperature from 500°F to 800°F were as follows for the 10,000 RPM designs:

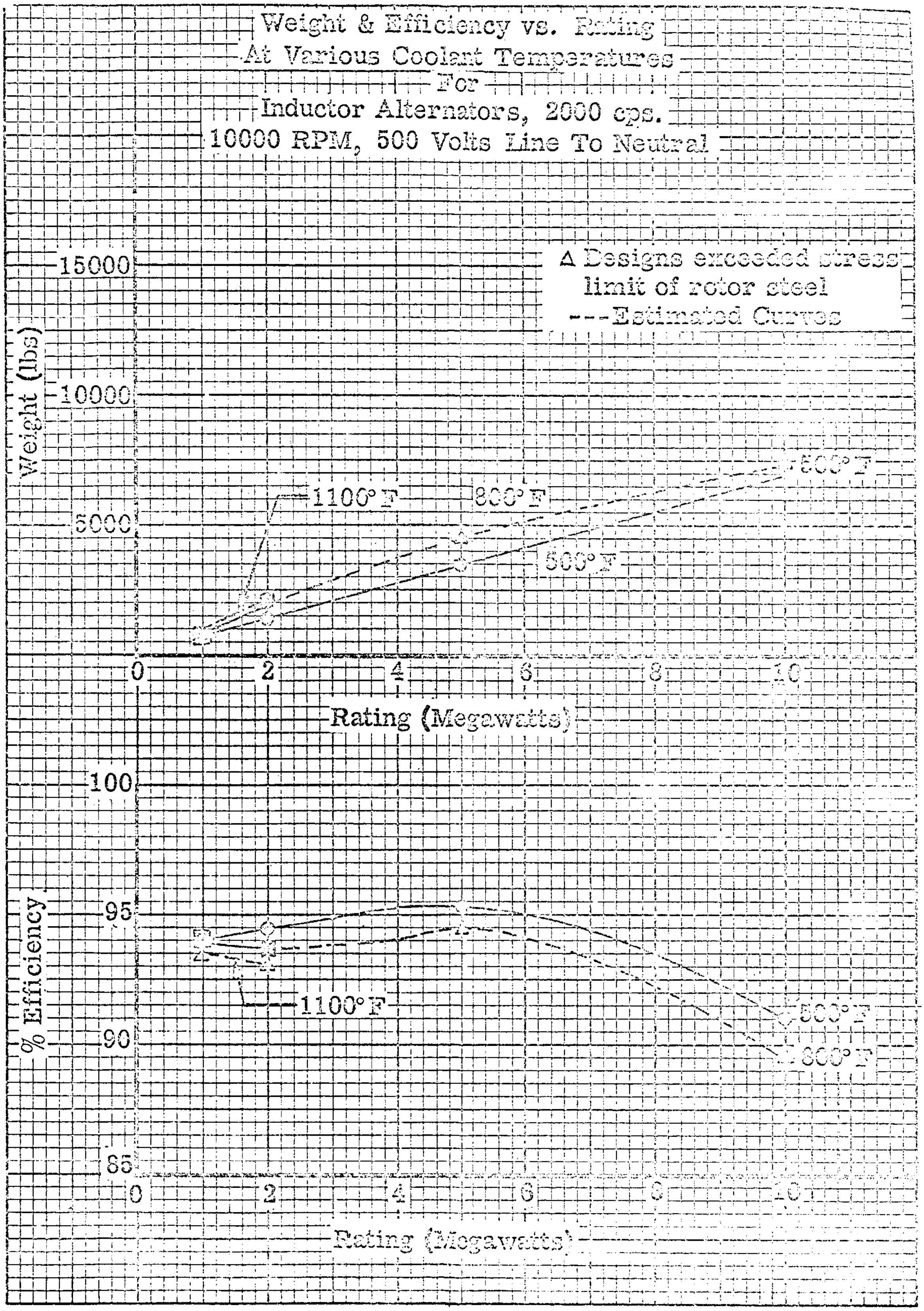


Figure 3.1.4-21

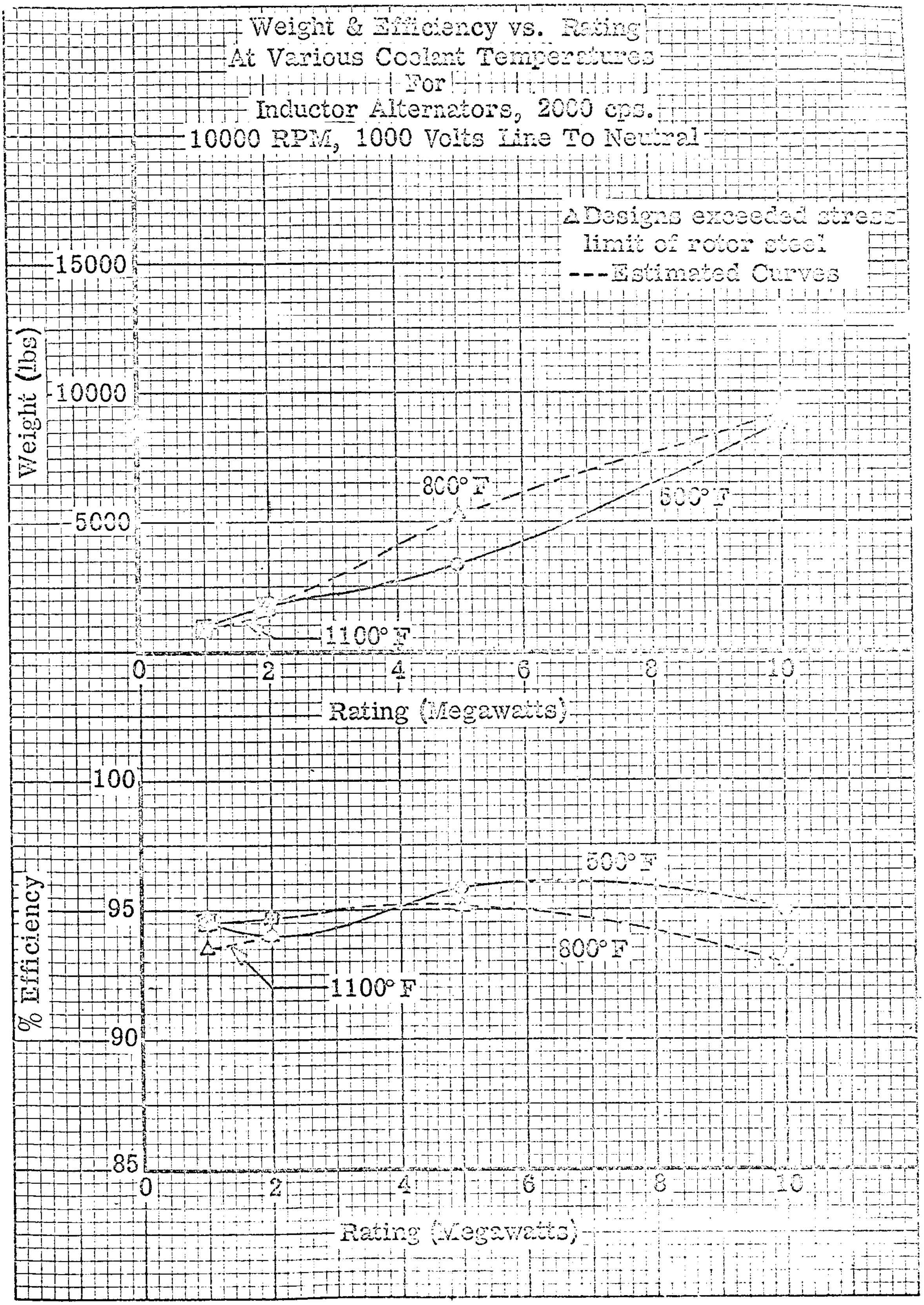


Figure 3. 1. 4-22

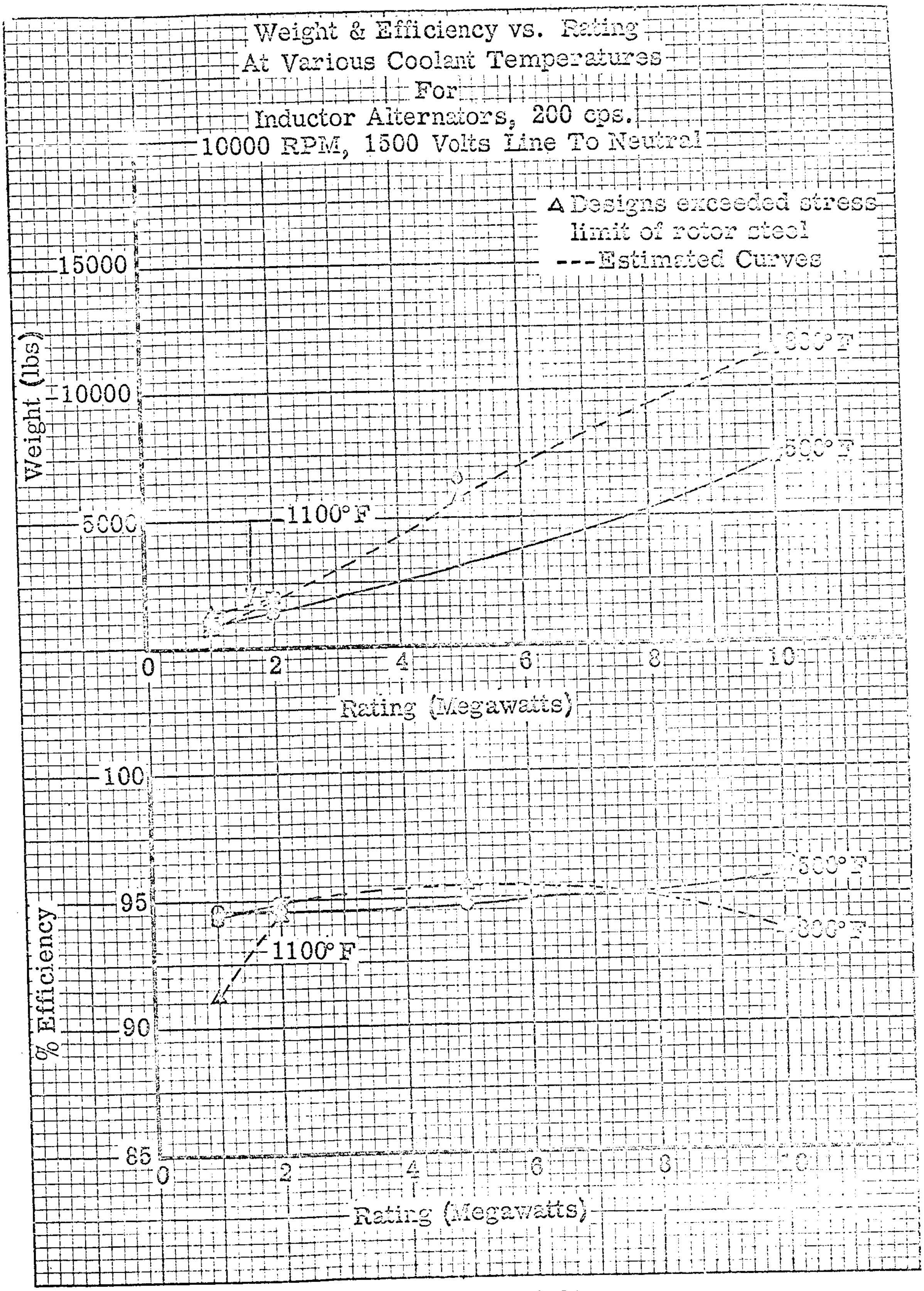


Figure 3.1.4-23

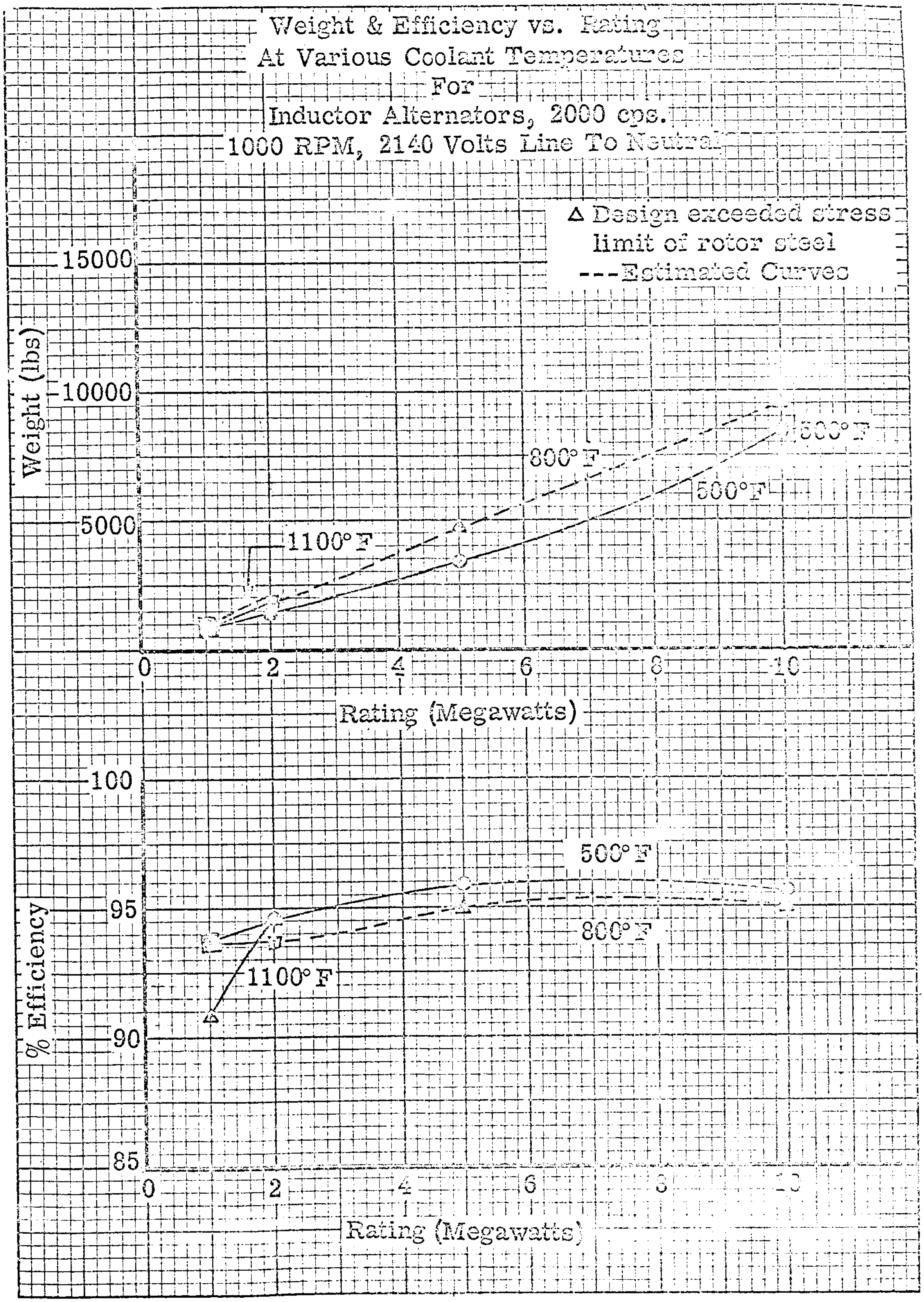


Figure 3.1.4-24

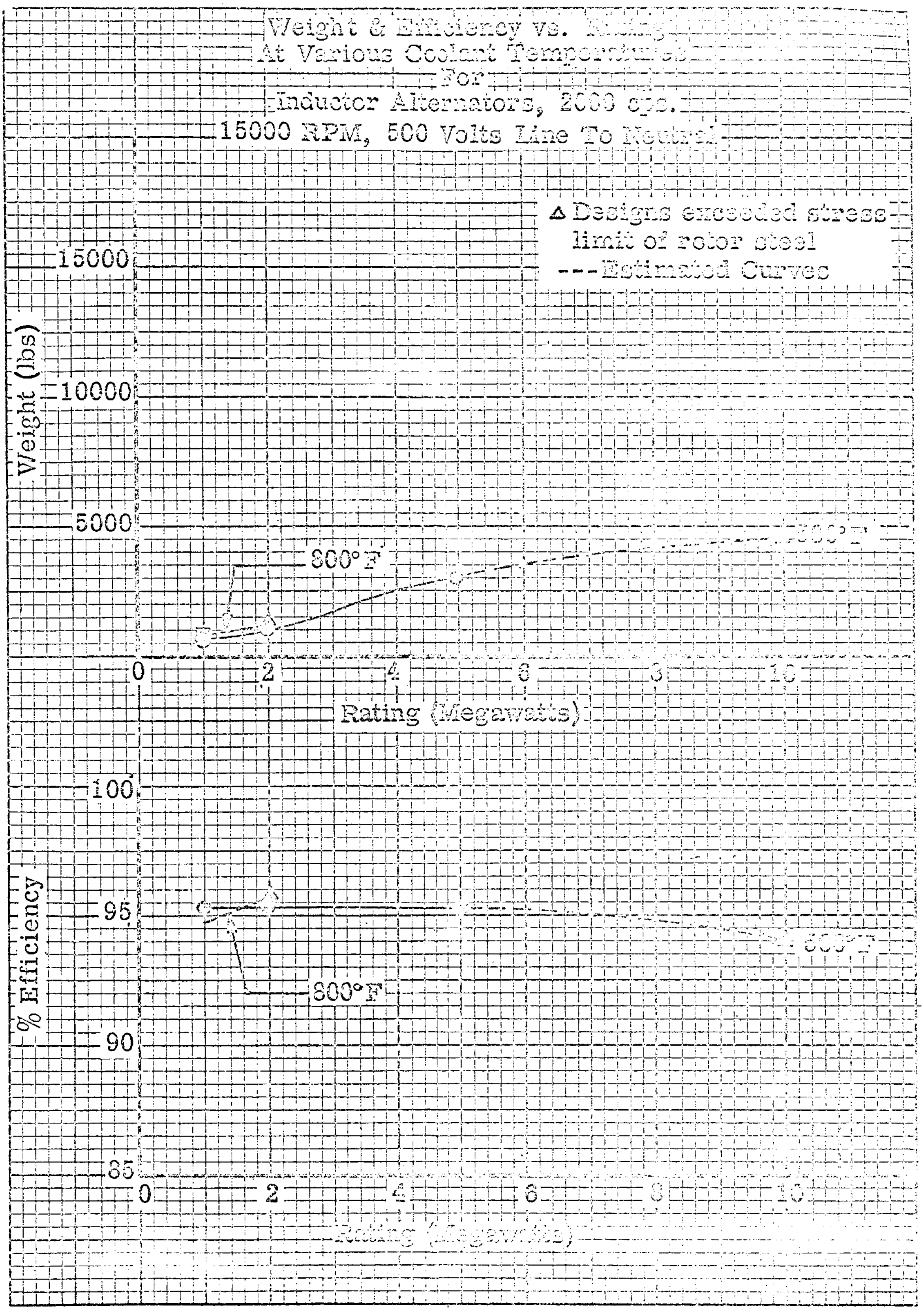


Figure 3. 1. 4-25

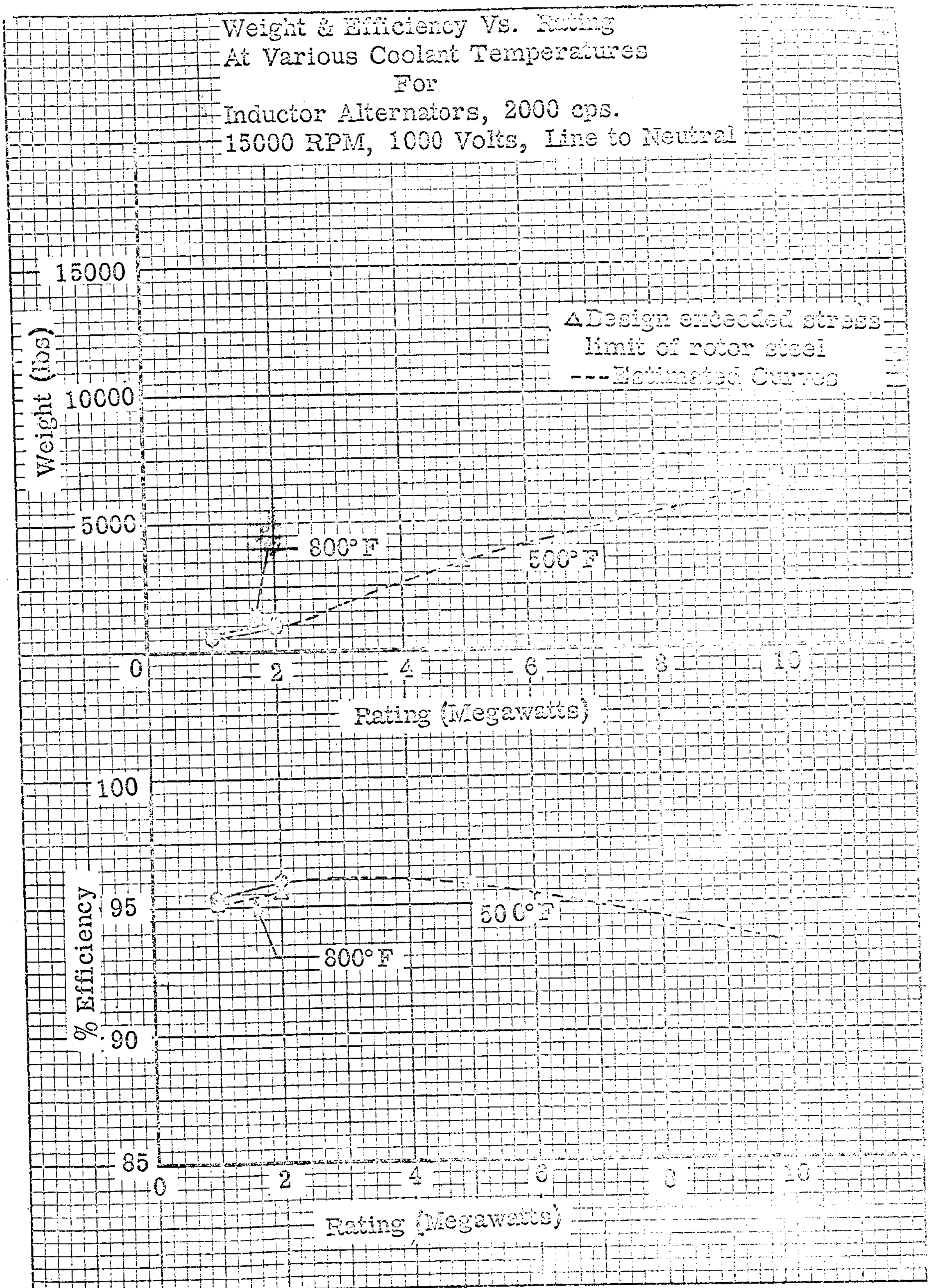


Figure 3.1.4-26

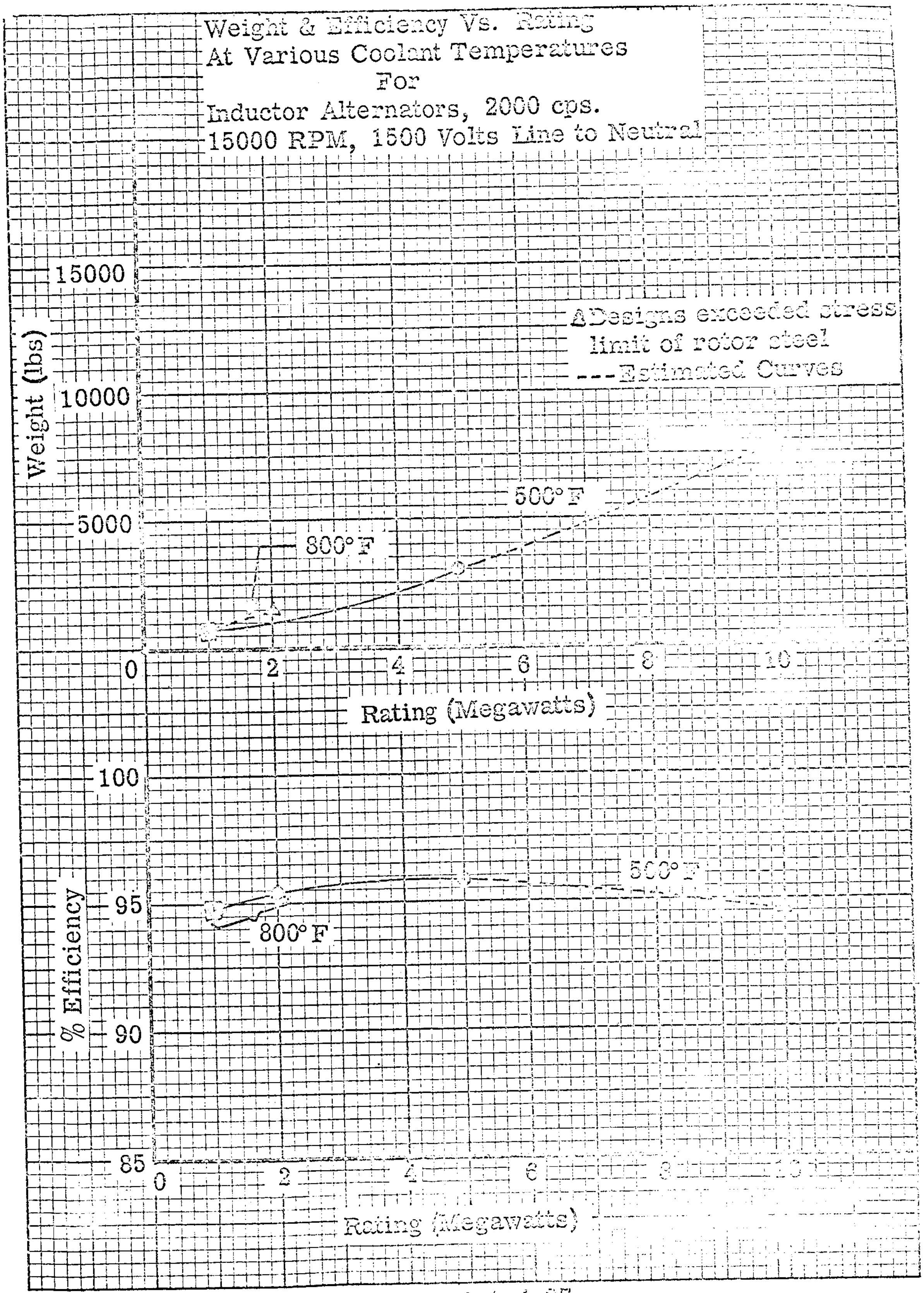


Figure 3. 1. 4-27

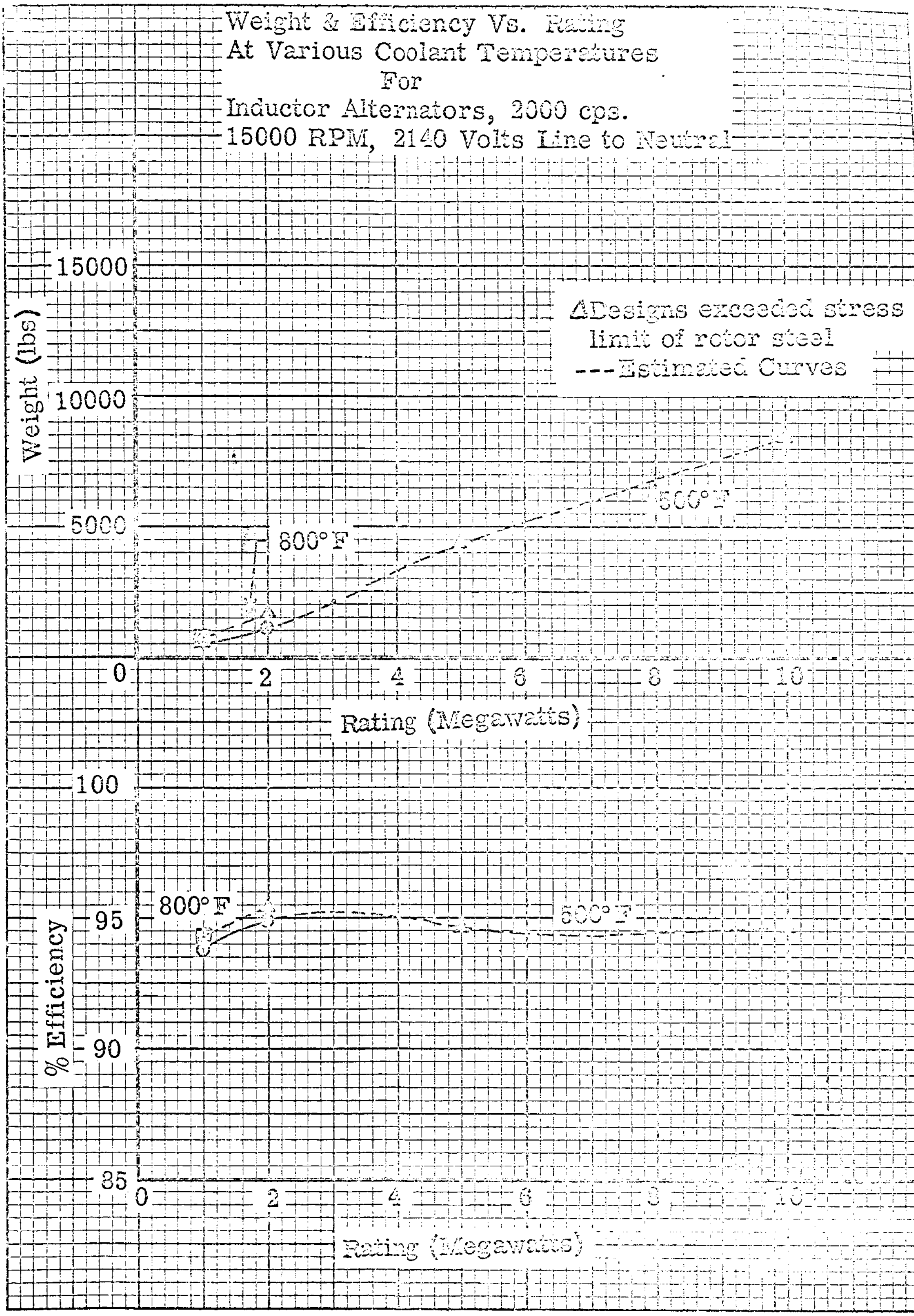


Figure 3. 1. 4-28

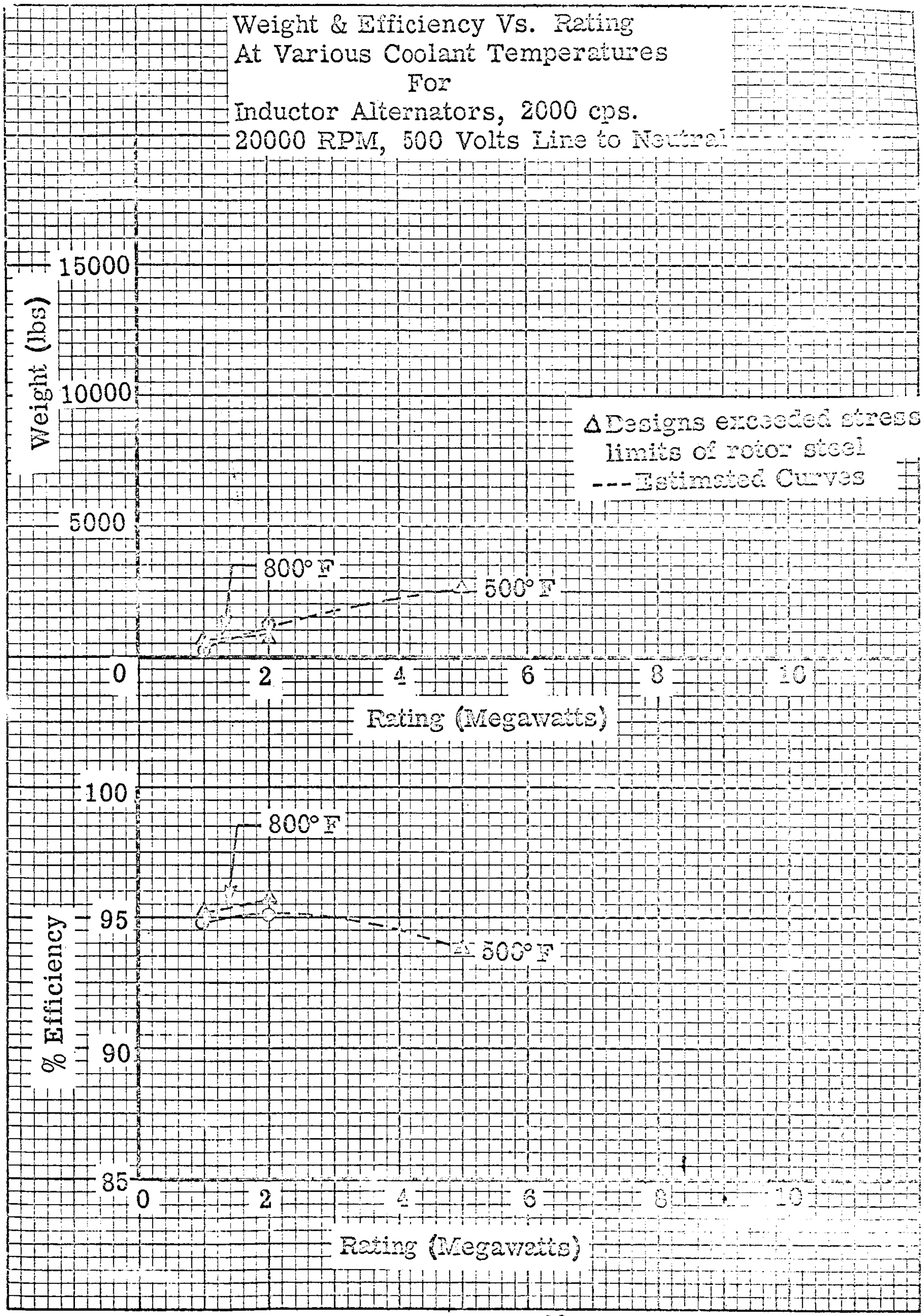


Figure 3.1.4-29

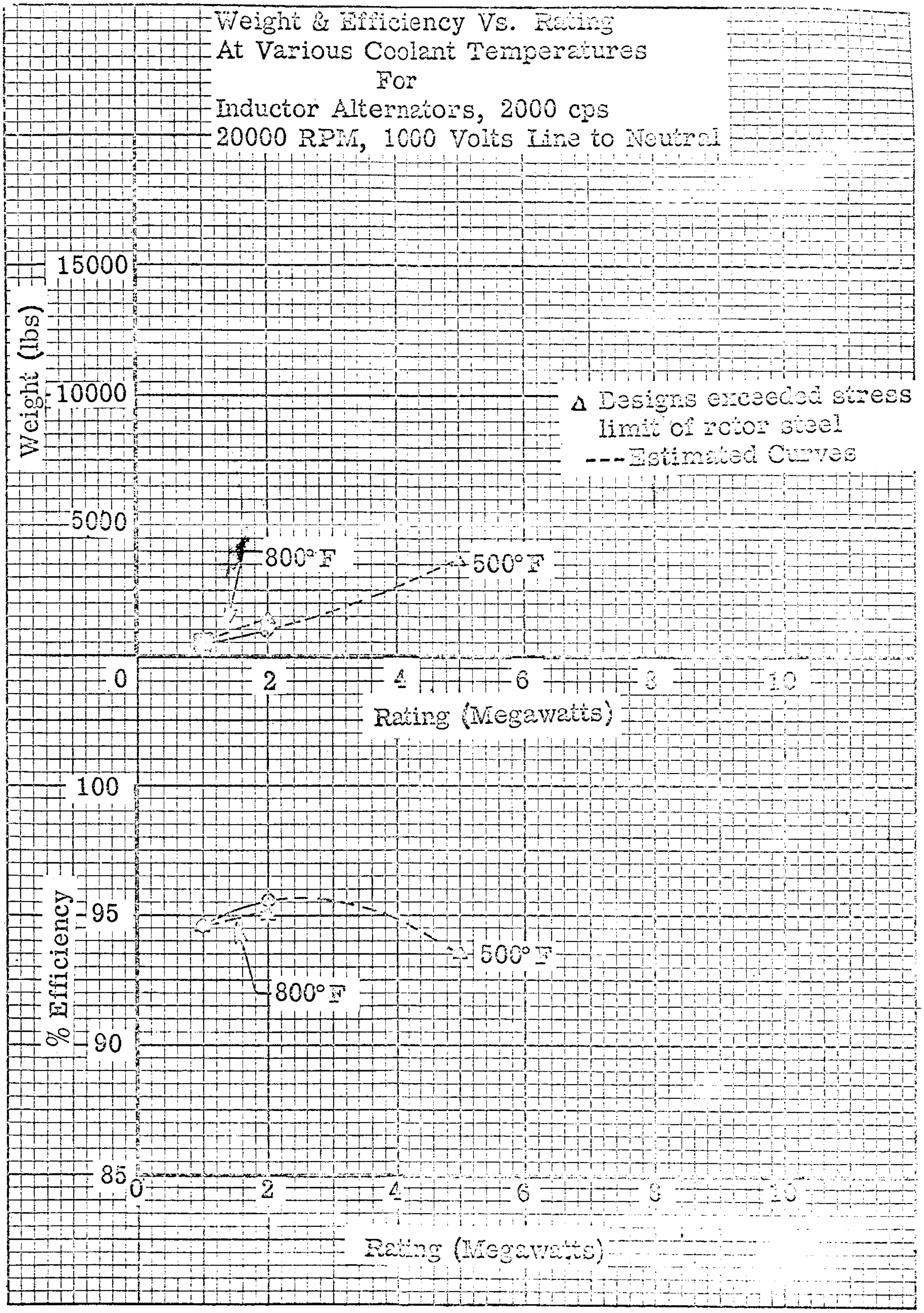


Figure 3.1.4-30

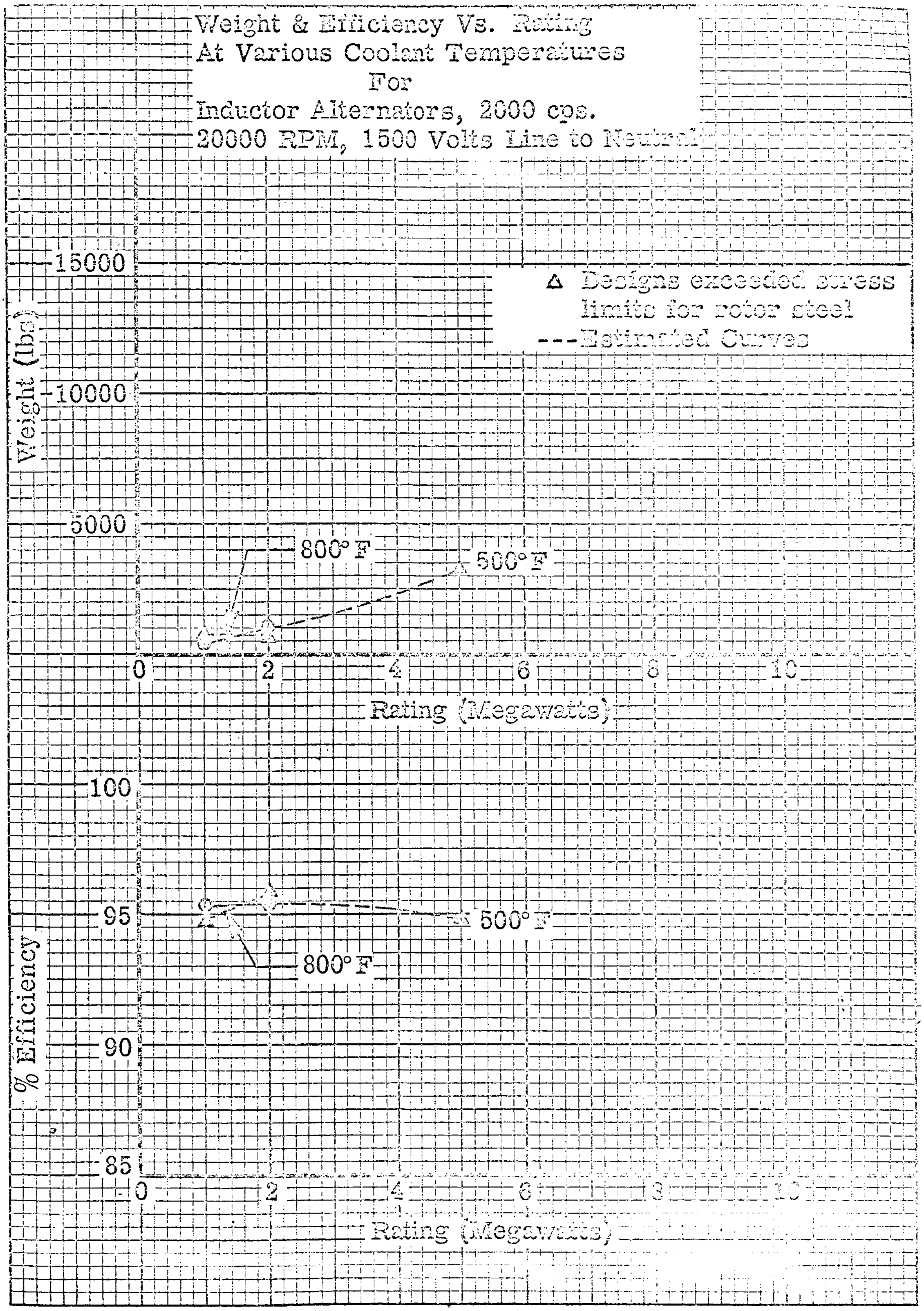


Figure 3.1.4-31

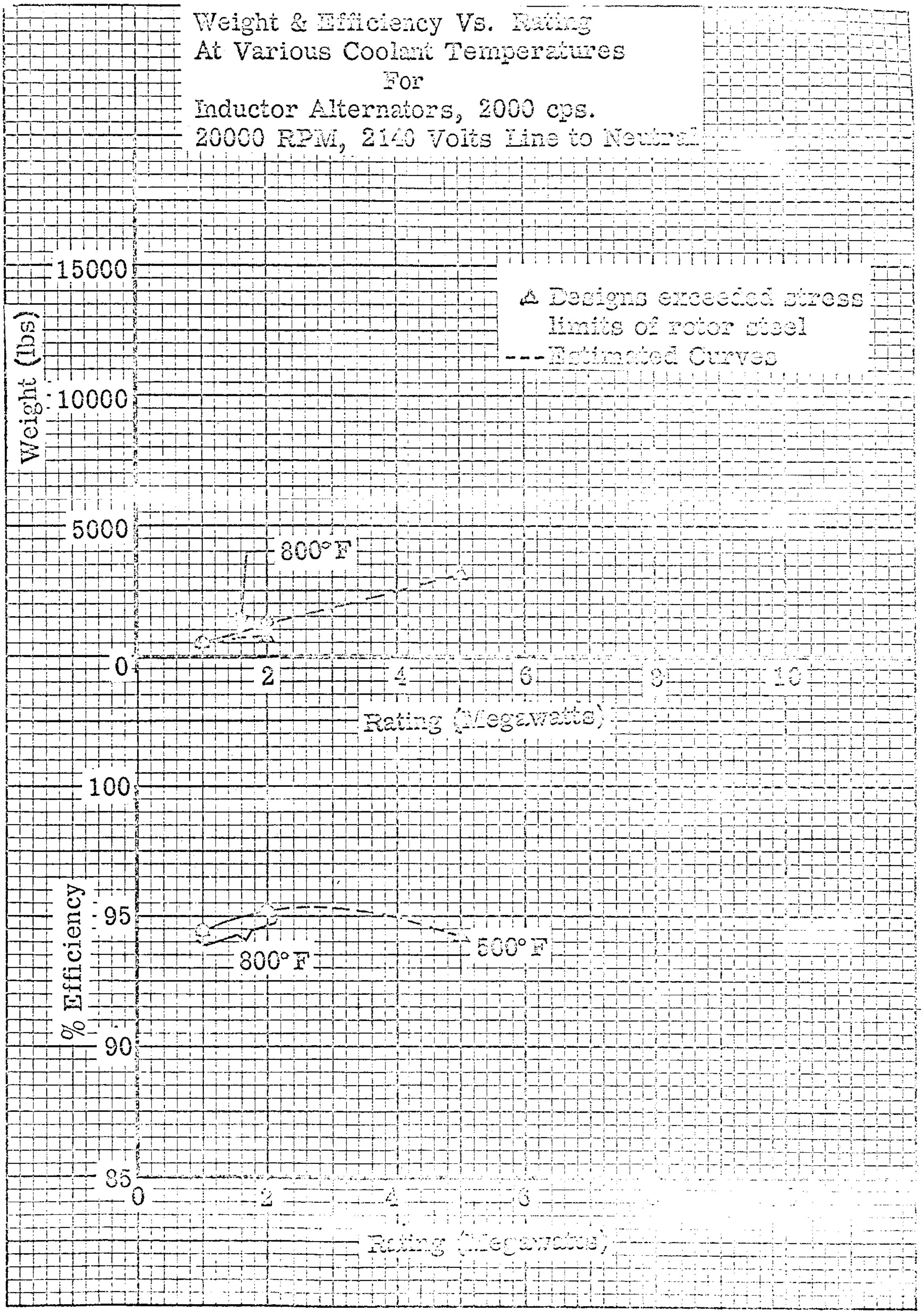


Figure 3.1.4-32

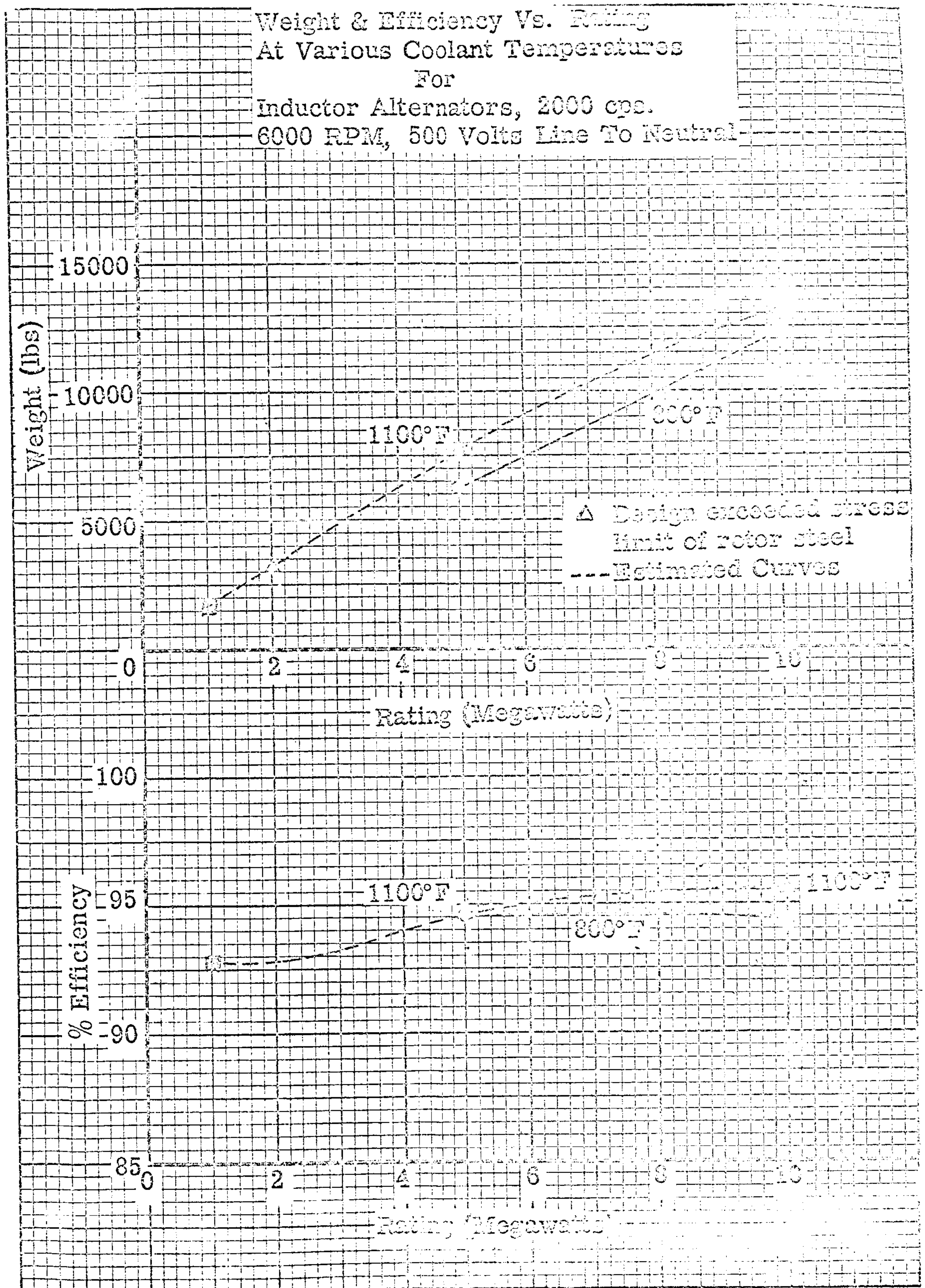


Figure 3. 1. 4-33

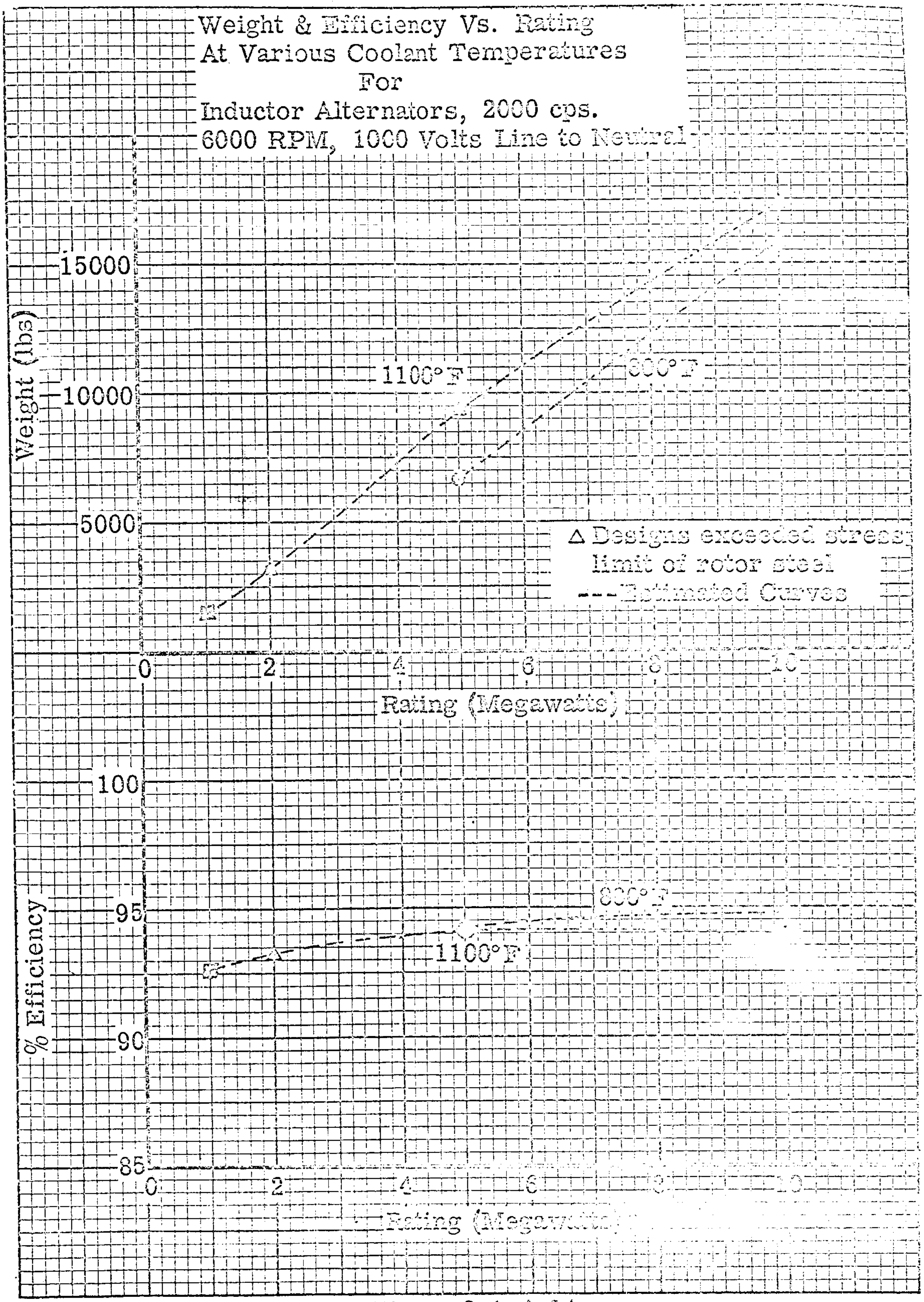


Figure 3.1.4-34

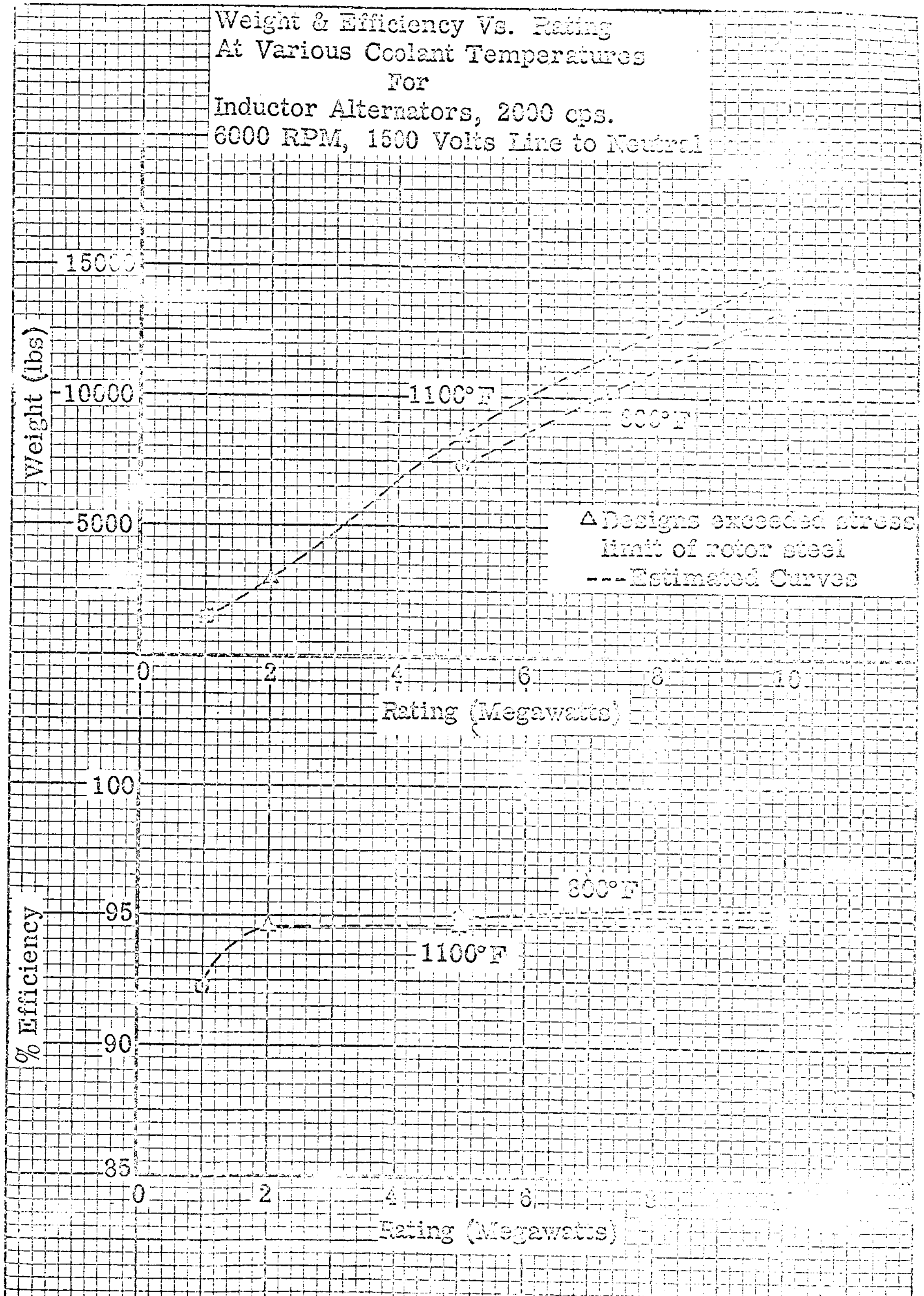


Figure 3. 1. 4-35

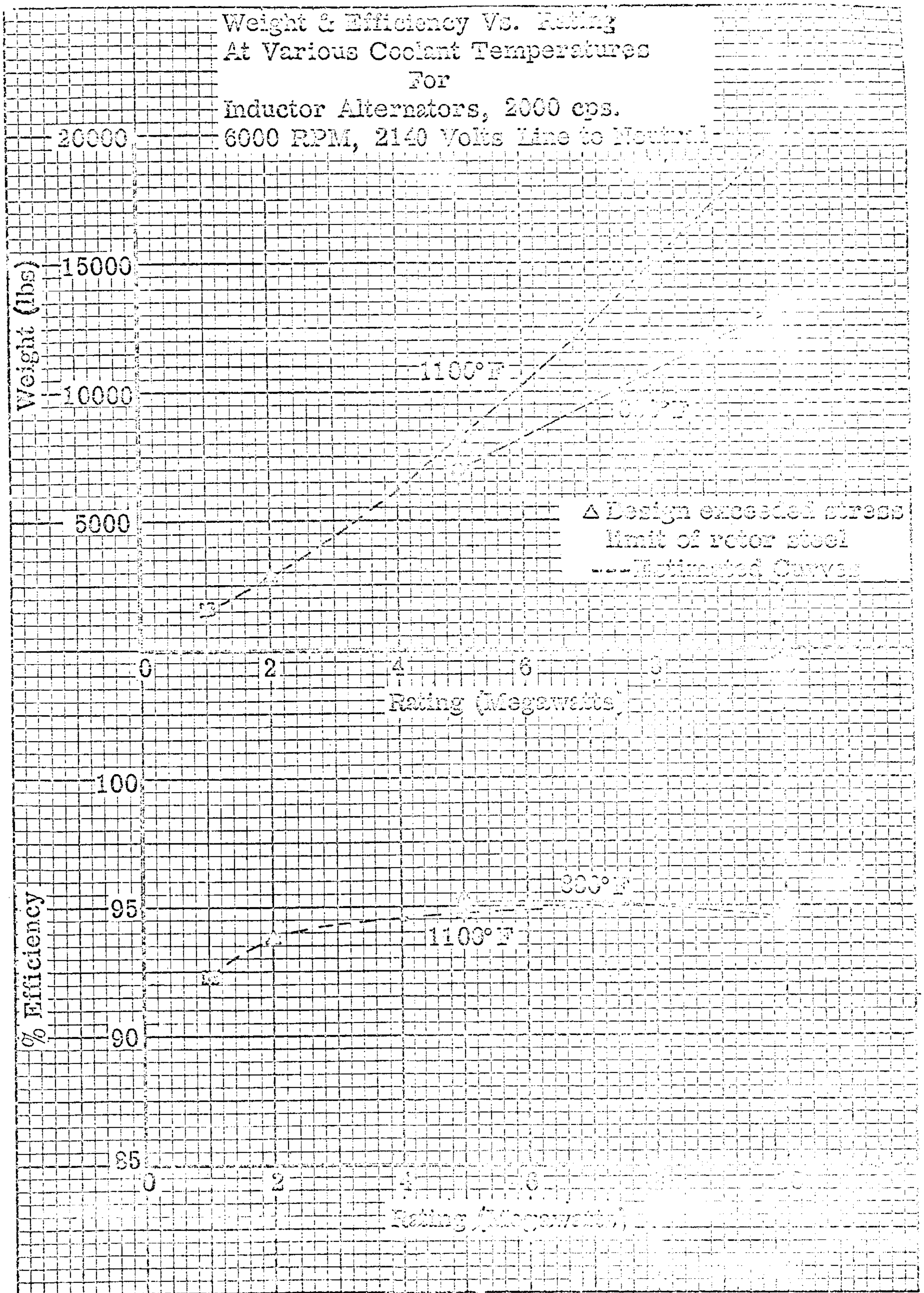


Figure 3. 1. 4-38

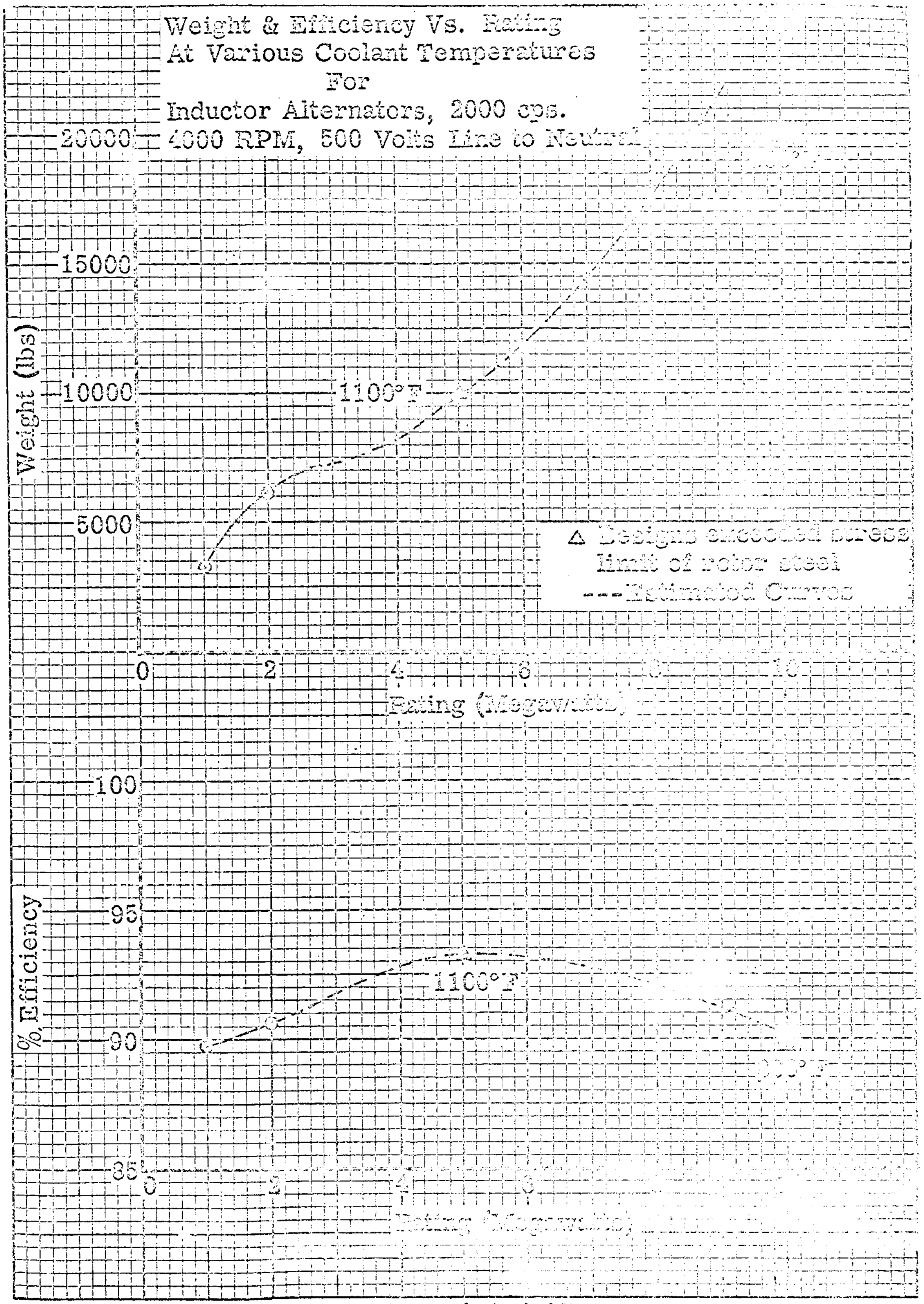


Figure 3.1.4-37

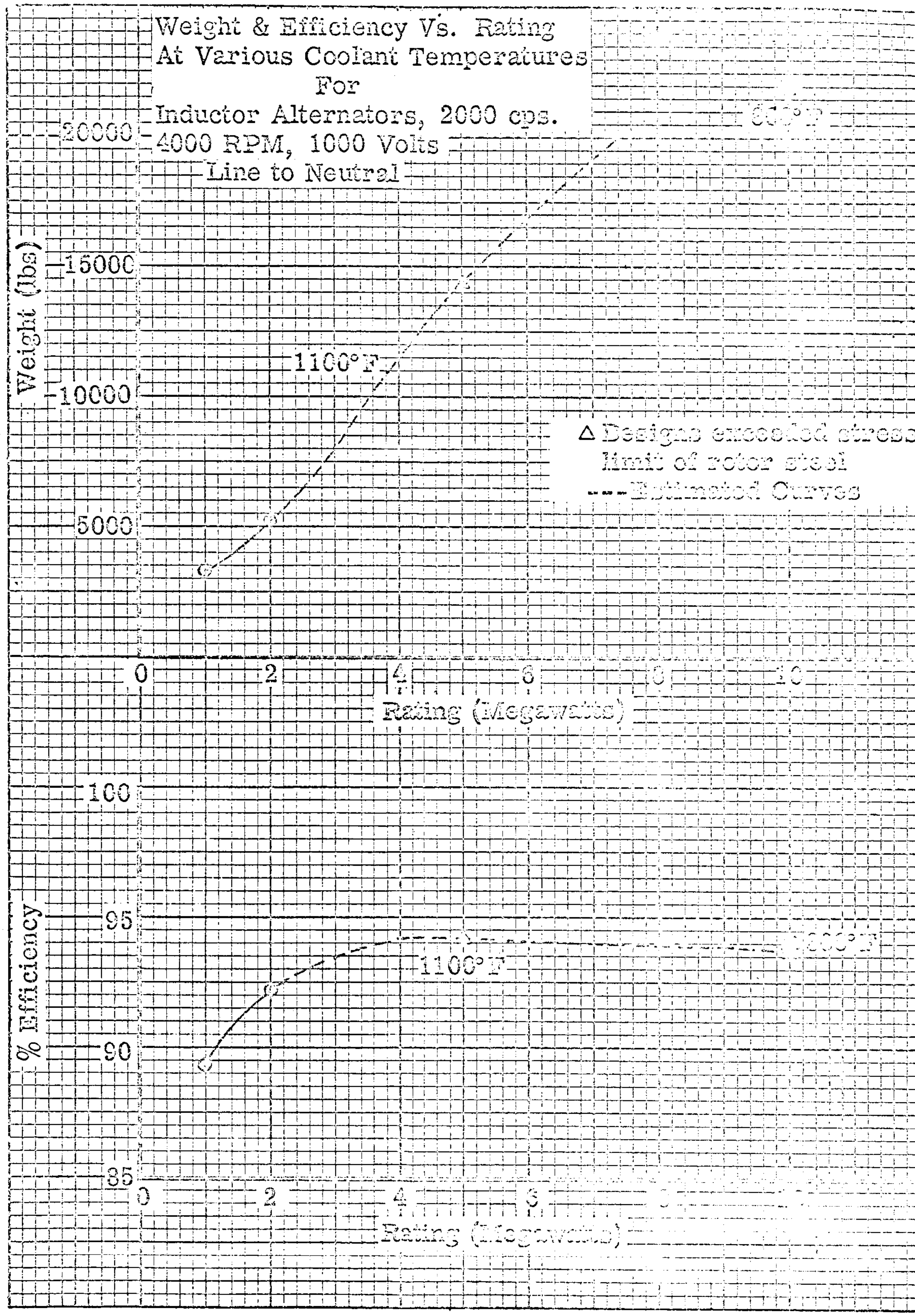


Figure 3.1.4-38

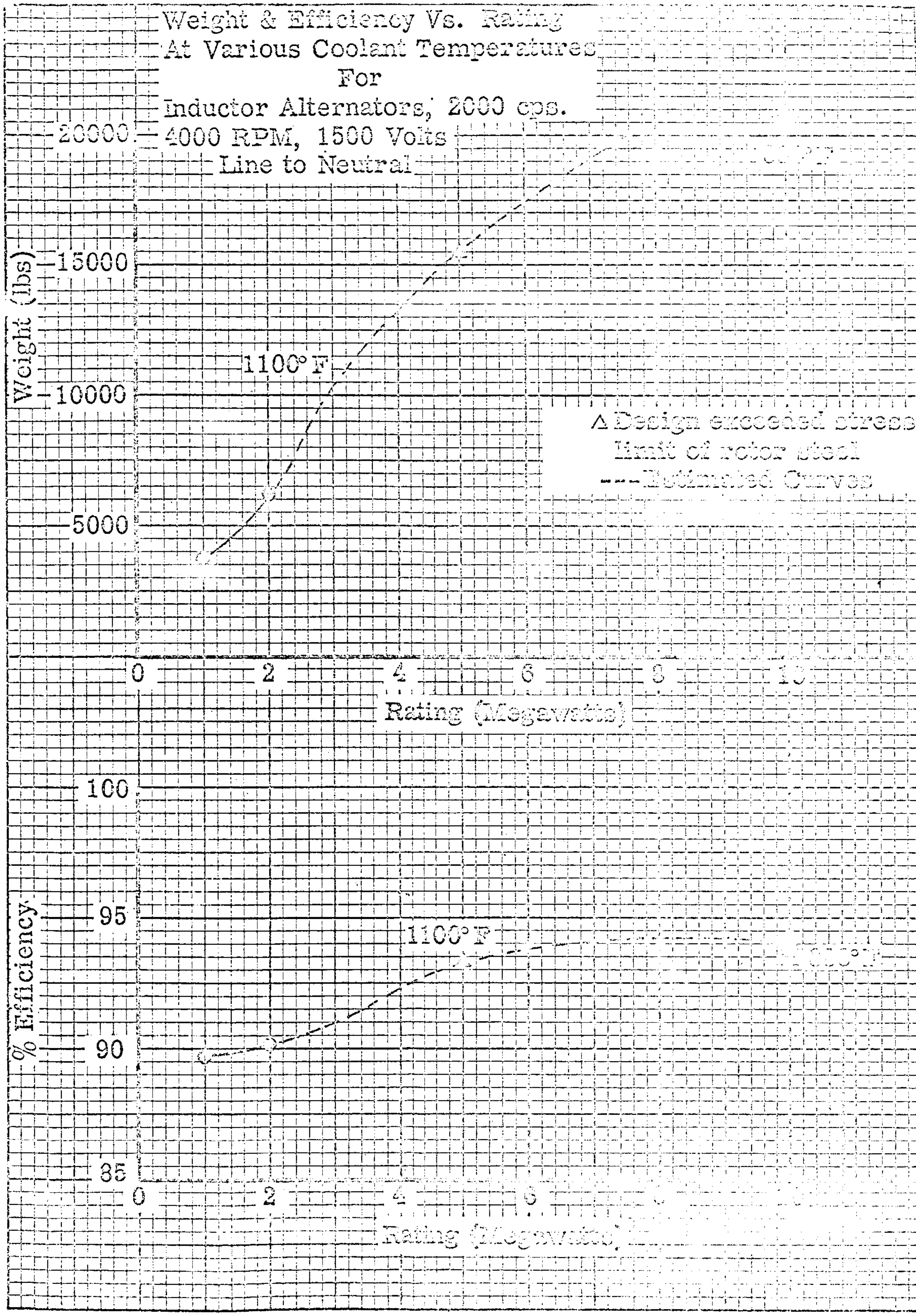


Figure 3. 1. 4-39

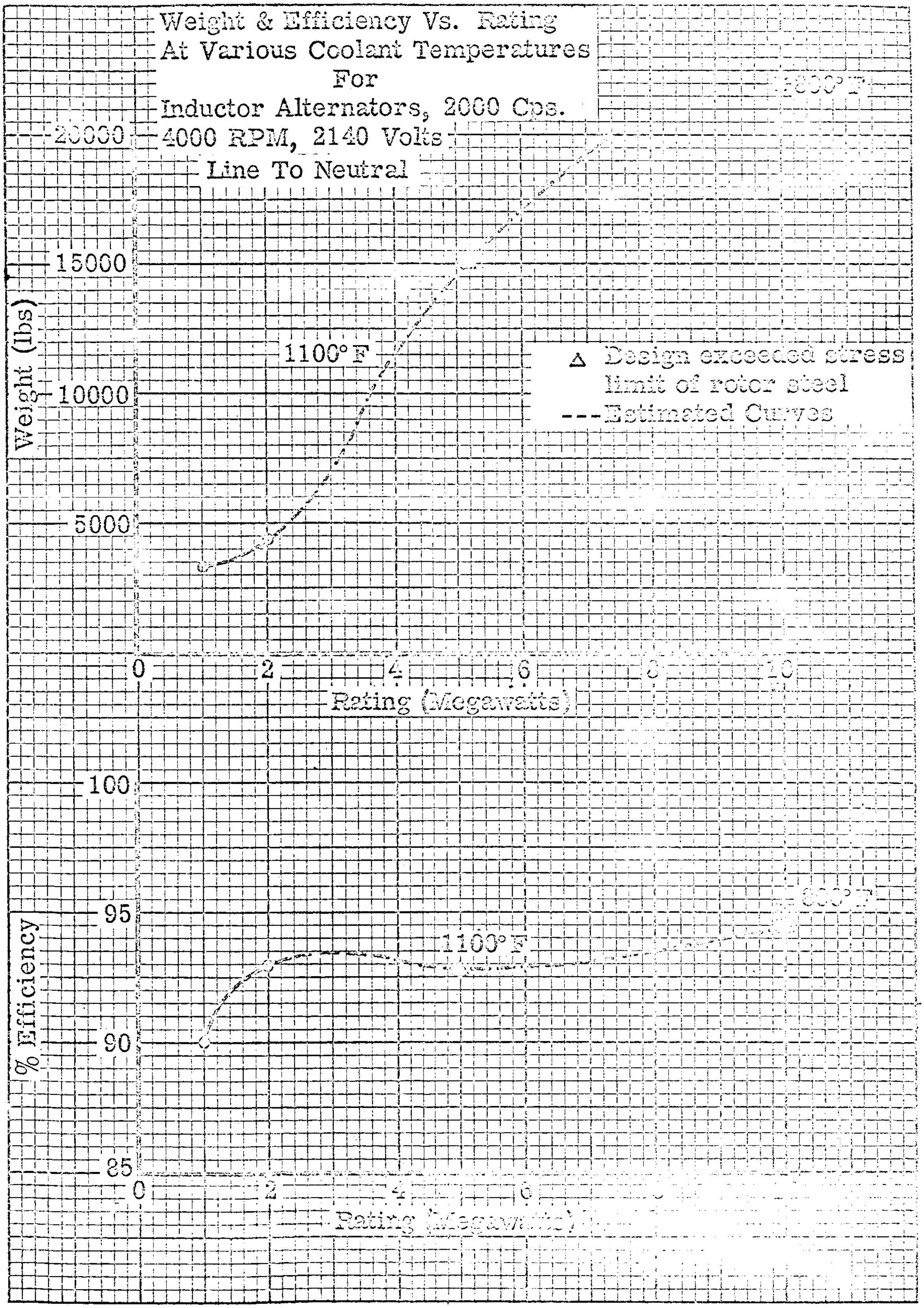


Figure 3. 1. 4-40

TABLE 3.1.4-4

Effect of Coolant Temperature on Weight and Efficiency

Following is a comparison of design points calculated at various average coolant temperatures. Designs marked with an * exceeded the rotor steel stress limits, but are shown for comparison to give an additional indication of the effects of temperature on weight and efficiency. As previously discussed, all 1500°F designs exceeded the rotor-steel stress limits, even at speeds as low as 2000 RPM.

	AVERAGE COOLANT TEMPERATURE					
	500°F		800°F		1100°F	
	AVERAGE LBS/KW	AVERAGE EFF.	AVERAGE LBS/KW	AVERAGE EFF.	AVERAGE LBS/KW	AVERAGE EFF.
20,000 RPM, 1 megawatt	.50	94.9	.552*	94.9*	-	-
20,000 RPM, 2 megawatts	.55	95.3	.517*	95.4*	-	-
15,000 RPM, 1 megawatt	.60	94.8	.65	94.8	-	-
15,000 RPM, 2 megawatts	.53	95.3	.62*	95.4*	-	-
15,000 RPM, 5 megawatts	.69	95.3	-	-	-	-
10,000 RPM, 1 megawatt	.80	94.4	.83	94.1	1.01*	92.5*
10,000 RPM, 2 megawatts	.73	93.4	.91	94.3	.89*	94.0*
10,000 RPM, 5 megawatts	.68	95.4	1.0*	95.0*	-	-
10,000 RPM, 10 megawatts	.75	94.4	.934*	92.9*	-	-
6,000 RPM, 1 megawatt	-	-	-	-	1.58	92.6
6,000 RPM, 2 megawatts	-	-	-	-	1.48*	93.6*
6,000 RPM, 5 megawatts	-	-	1.37	94.7	1.66*	94.5*
6,000 RPM, 10 megawatts	-	-	1.38	94.8	1.77*	94.9*

TABLE 3.1.4-4 (Cont'd)

Effect of Coolant Temperature on Weight and Efficiency

	500°F		800°F		1100°F	
	AVERAGE LBS/KW	AVERAGE EFF.	AVERAGE LBS/KW	AVERAGE EFF.	AVERAGE LBS/KW	AVERAGE EFF.
4000 RPM, 1 megawatt	-	-	-	-	3.31	89.7
4000 RPM, 2 megawatts	-	-	-	-	2.75	91.6
4000 RPM, 5 megawatts	-	-	-	-	2.75*	93.5*
4000 RPM, 10 megawatts	-	-	2.14	93.1	2.49*	93.2

1 megawatt: 4% avg. weight increase; 0.3% avg. eff. decrease.

2 megawatt: 25% avg. weight increase; 0.9% avg. eff. increase.

5 megawatt: 47% avg. weight increase; 0.4% avg. eff. decrease.

10 megawatt: 24% avg. weight increase; 1.5% avg. eff. decrease.

From the above, it is concluded that one-megawatt-generator coolant temperatures of 500°F and 800°F result in nearly equal weights and efficiencies. A two-megawatt generator coolant temperature of 500°F results in the lightest weight; however, at 800°F an efficiency increase of about 1% can be obtained. The five and ten-megawatt, 10,000 RPM, designs show a greater effect of higher coolant temperatures on weight and efficiency.

At 15,000 RPM the one-megawatt, 800°F designs, show an 8% higher average weight and the same average efficiency as the 500°F designs. The two-megawatt, 15,000 RPM, 800°F designs and the one and two-megawatt, 20,000 RPM, 800°F designs exceeded the stress limit of the rotor steel. If these 800°F designs were made practical by increased rotor-steel strength, the increase from 500°F to 800°F would require a weight penalty of about 10% at 20,000 RPM and a weight penalty of about 15% at 15,000 RPM. There is little difference in average efficiencies between the 500°F and 800°F designs at these speeds.

No one or two-megawatt designs were calculated at 6000 RPM or 4000 RPM for temperatures under 1100°F, because practical 500°F and 800°F designs were obtained at higher speeds. Likewise, no five or ten-megawatt designs were calculated at 6000 or 4000 RPM for temperatures under 800°F, because practical 500°F designs were obtained at higher speeds. At 1100°F, practical

6000 RPM generator ratings are limited to one megawatt. At 800°F, some practical designs were obtained at ratings up to ten megawatts. Table 3.1.4-4 shows that a generator weight increase of 20% to 30% would be required in going from 800°F to 1100°F if material were available to make the higher temperature five and ten-megawatt, 6000 RPM designs practical. Changes in efficiencies would be small. A weight increase of about 15% would be required in going from 800°F to 1100°F for ten-megawatt, 4000 RPM generators, if material with sufficient strength at 1100°F was available.

3.2 Electrical Conversion and Control

This section provides parametric data for the generator-excitation control, switch gear and tap-changing circuitry, power-conversion circuitry, and transformer.

3.2.1 Static-Exciter-Voltage Regulators

Voltage regulators used to control a-c generators must have the capability of supplying the necessary excitation to maintain the generator terminal voltage at the desired level. For generators which require large amounts of excitation power, it is important that the excitation and control system be able to furnish the required power and at the same time, have low power dissipation within the regulator. There are several circuits which may be used to control the excitation to the generator. The advantages and disadvantages of each will be discussed and calculations of weights and power losses will be made to select the best circuit for supplying excitation for generators with ratings of 1, 5, and 10 megawatts. Table 3.2.1-1 lists the preliminary generator designs used in the exciter-regulator calculation for this report.

An exciter-regulator must perform three basic functions to control the generator excitation: (1) detect any error in generator output; (2) amplify this error signal and furnish a control signal to the power stage; (3) supply the proper amount of excitation to the generator field through the power stage to maintain the generator output at the desired level. This report will deal with (2) and (3) since (1) will be essentially independent of the generator excitation requirements.

All exciter-regulators considered in this study utilize the cold-plate type of package design with a circulating coolant fluid to accomplish component cooling.

TABLE 3.2.1-1

PRELIMINARY GENERATOR DESIGNS - 2000 cps

DESIGN NO.	COOL-ANT TEMP. (^{o}F)	SPEED (RPM)	GEN. VOLTS L-N	% EFFI-CIENCY	GEN. WT. (LBS)	MAX. GEN. O.D. (IN)	TO-TAL GEN. LGTH. (IN)	P.U. X_d	EXCITATION POWER (KW) AT RATED LOAD
A 1 Mega-watt	500	10,000	2140	93.6	803	25.3	13.15	1.03	6.72
B 5 Mega-watts	500	10,000	2140	95.2	4117	34.8	31.8	1.25	8.89
C 10 Mega-watts	500	10,000	2140	95.7	8440	41.9	40.8	1.30	10.61

3.2.1.1 Silicon-Controlled-Rectifier Exciter-Regulator

Power Stage

The following circuits have been selected as the most promising for the applications required by this study: three-phase half-wave utilizing 3 silicon controlled rectifiers; three-phase full-wave utilizing three silicon controlled rectifiers and three silicon rectifiers; six-phase half-wave, and three-phase double-wye. The last two require six silicon controlled rectifiers. Listed below are advantages and disadvantages of each.

Three Phase Half Wave Circuit

Advantages:

1. Only three silicon controlled rectifiers are required.
2. The silicon-controlled-rectifier, gate-control circuit is not as complex as the one required for the six-phase circuits.
3. Three-phase transformers are required for power and control circuits which have fewer windings and connections than six-phase or three-phase double-wye.

Disadvantages:

1. High peak inverse voltages are impressed across each rectifier for a given d-c voltage output.
2. The d-c components in the transformer caused by this circuit tend to saturate the transformer core since they flow only in one direction.
3. Each rectifier must carry 1/3 the d-c output current.

Three-Phase Full-Wave Circuit

Advantages:

1. The peak-inverse-voltage impressed across each rectifier is low for a given d-c output voltage. Almost twice the d-c voltage output can be obtained for a given peak-inverse-voltage rating for this type circuit than for other circuits.

2. The power transformer has high primary and secondary utilization factors. (Utilization factor (UF) is defined as the ratio of d-c power output from the rectifier circuit to the required volt-ampere capacity of the transformer.)

3. There is no d-c saturation of the power transformer since the d-c components flow in opposite directions in the windings and cancel out.

4. The silicon-controlled-rectifier gate control circuit is not complex since only three rectifiers must be controlled.

Disadvantages:

1. There are two rectifiers conducting in series with the resultant added voltage drop.

2. Each rectifier must carry 1/3 of the d-c output current.

Six-Phase Half-Wave Circuit

Advantages:

1. The d-c components in the power transformer windings cancel, thus avoiding any tendency toward transformer-core saturation.

2. Each rectifier must carry only 1/6 of the d-c output current.

Disadvantages

1. The peak-inverse voltage impressed across each rectifier is high for a given d-c output voltage.

2. The transformer utilization factors are low. (UF_p = 0.78 and UF_s = 0.551).

3. The gate control circuit is more complex since 6 rectifiers must be controlled.

4. Six-phase power and control transformers are required.

5. The rectifier utilization is lower since the maximum conduction angle is 60 degrees compared to 120 degrees for the other circuits.

Three-Phase Double-Wye Circuit

Advantages:

1. The power output capability is high.

2. The transformer utilization factor is high (UF_p = 0.955 and UF_s = 0.675)

3. The diode utilization is high since two rectifiers conduct in parallel for 120 degrees at load currents above the transition load current.

Disadvantages:

1. The gate control circuit is more complex than for 3-phase, half-wave or 3-phase full-wave since 6 rectifiers must be controlled.

2. Two three-phase transformers with an interphase transformer are required.

3. There is a possibility that unwanted variations in the power output will occur since the rectifiers will conduct for only 60° at low load

currents, but will switch into 120° conduction at the transition load current. (This transition point is dependent upon the interphase transformer design.)

Because of the possibility of unwanted variations in output power due to transition from 60 degrees to 120 degrees conduction at the transition load current, the three-phase, double-wye circuit appears undesirable and will not be considered further.

Figures 3.2.1-1 through 3.2.1-6 show the theoretical output voltage and output power characteristics as a function of firing angle for three-phase half-wave, three-phase full-wave, and six-phase half-wave circuits. The curves were calculated assuming perfect rectifiers (no voltage drop), perfect commutation (no overlap), and a pure resistive load. For figures 3.2.1-1, 3.2.1-3, 3.2.1-4 and 3.2.1-6 the rms line-to-neutral voltage is that applied to the rectifiers while figure 3.2.2-2 is plotted as a function of the line-to-line voltage applied to the rectifiers. The resistance, R, for figures 3.2.1-4, 3.2.1-5 and 3.2.1-6 is the load resistance. The firing angle is defined as the point in the positive half cycle of a sine wave at which the silicon controlled rectifier is switched into the conducting state by a gate control signal.

Calculations of exciter-regulator weight and power loss were made for the three-phase half-wave, three-phase full-wave, and six-phase half-wave circuits and their associated control circuits. In all cases, the calculations were based upon derating the peak inverse voltage rating of the rectifiers by a factor of two and derating their critical junction temperatures by at least

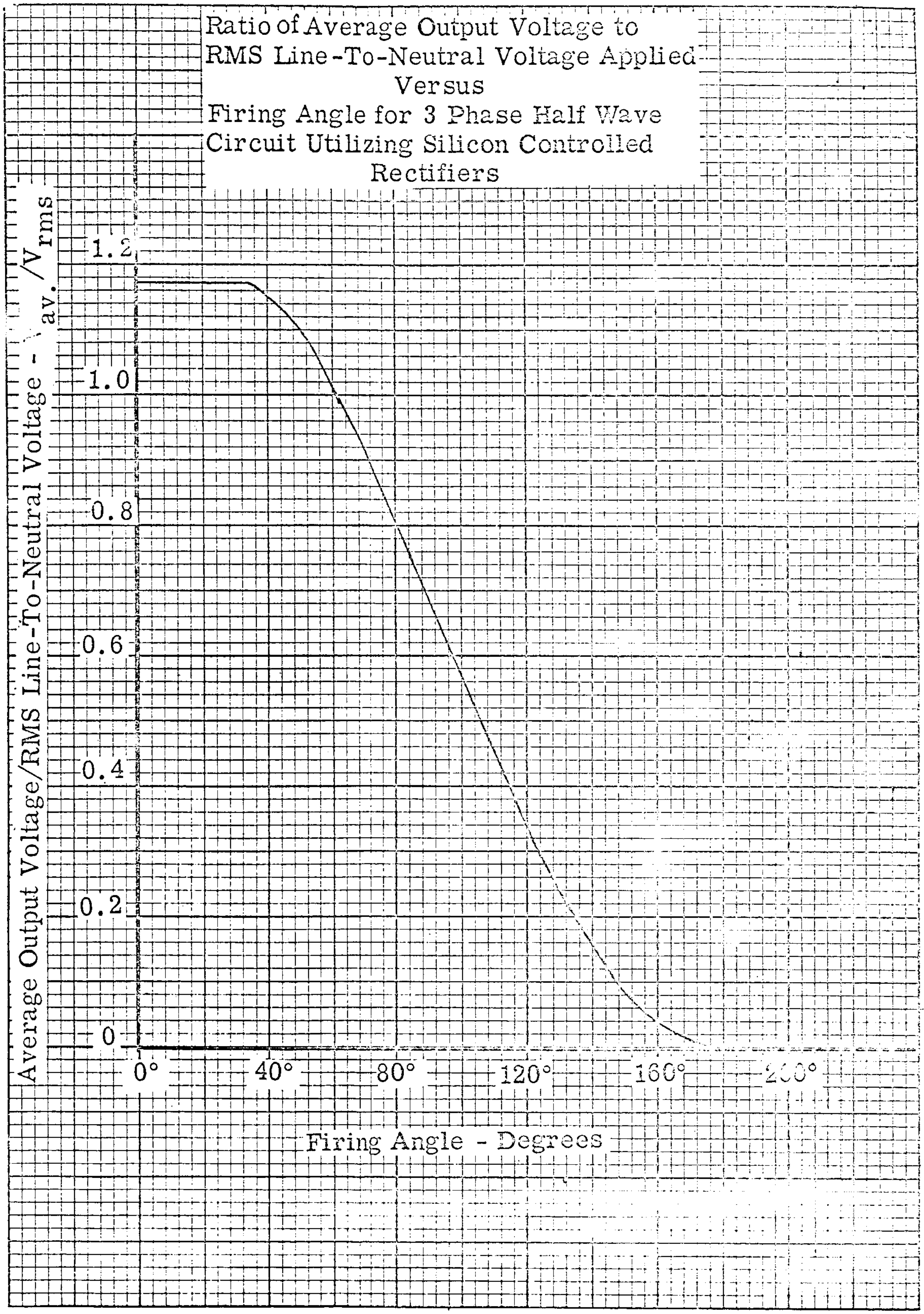

Ratio of Average Output Voltage to
RMS Line-To-Neutral Voltage Applied
Versus
Firing Angle for 3 Phase Half Wave
Circuit Utilizing Silicon Controlled
Rectifiers
Average Output Voltage/RMS Line-To-Neutral Voltage - $V_{av.}/V_{rms}$
1.2
1.0
0.8
0.6
0.4
0.2
0
0°
40°
80°
120°
160°
200°
Firing Angle - Degrees

Figure 3. 2. 1-1

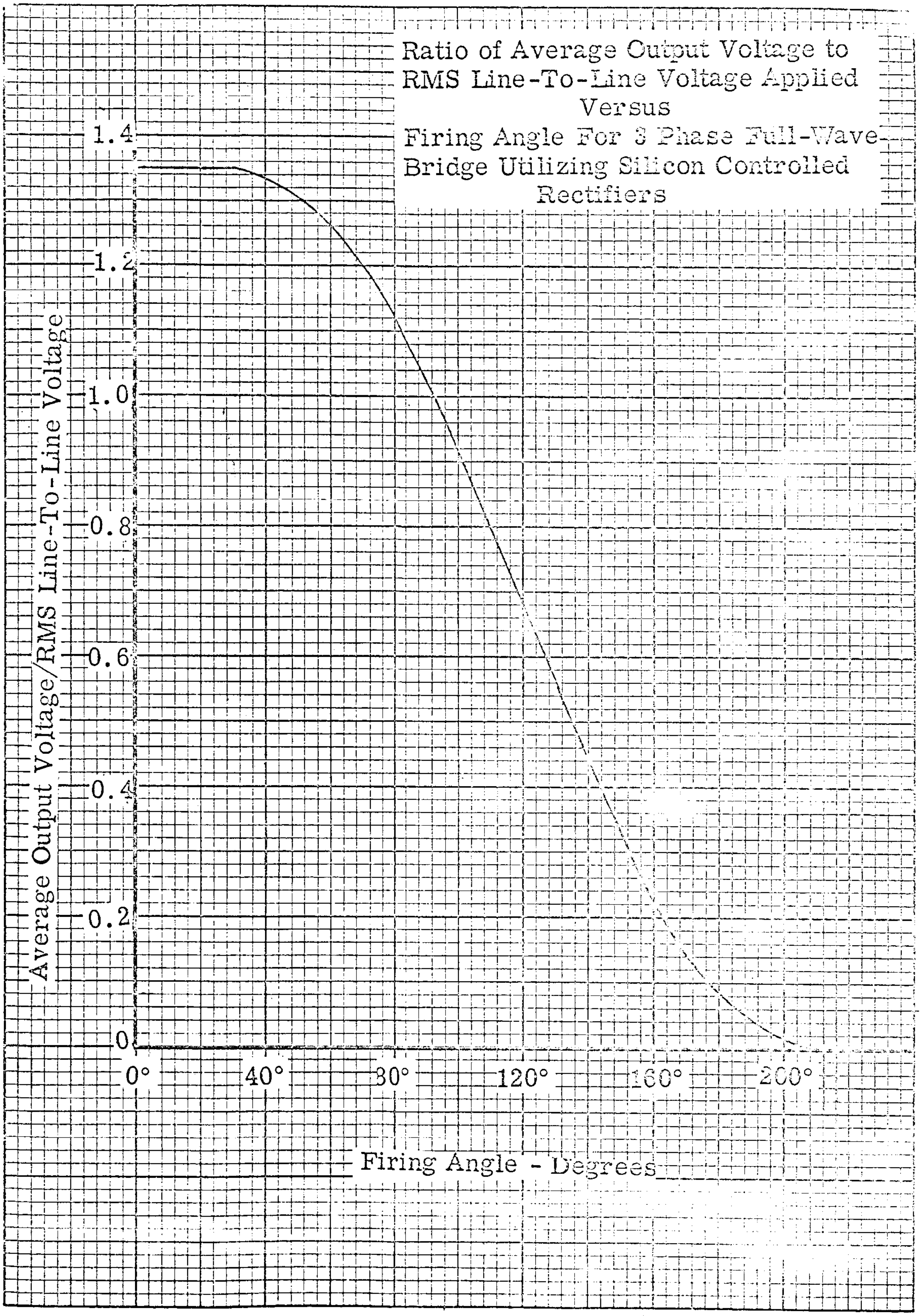
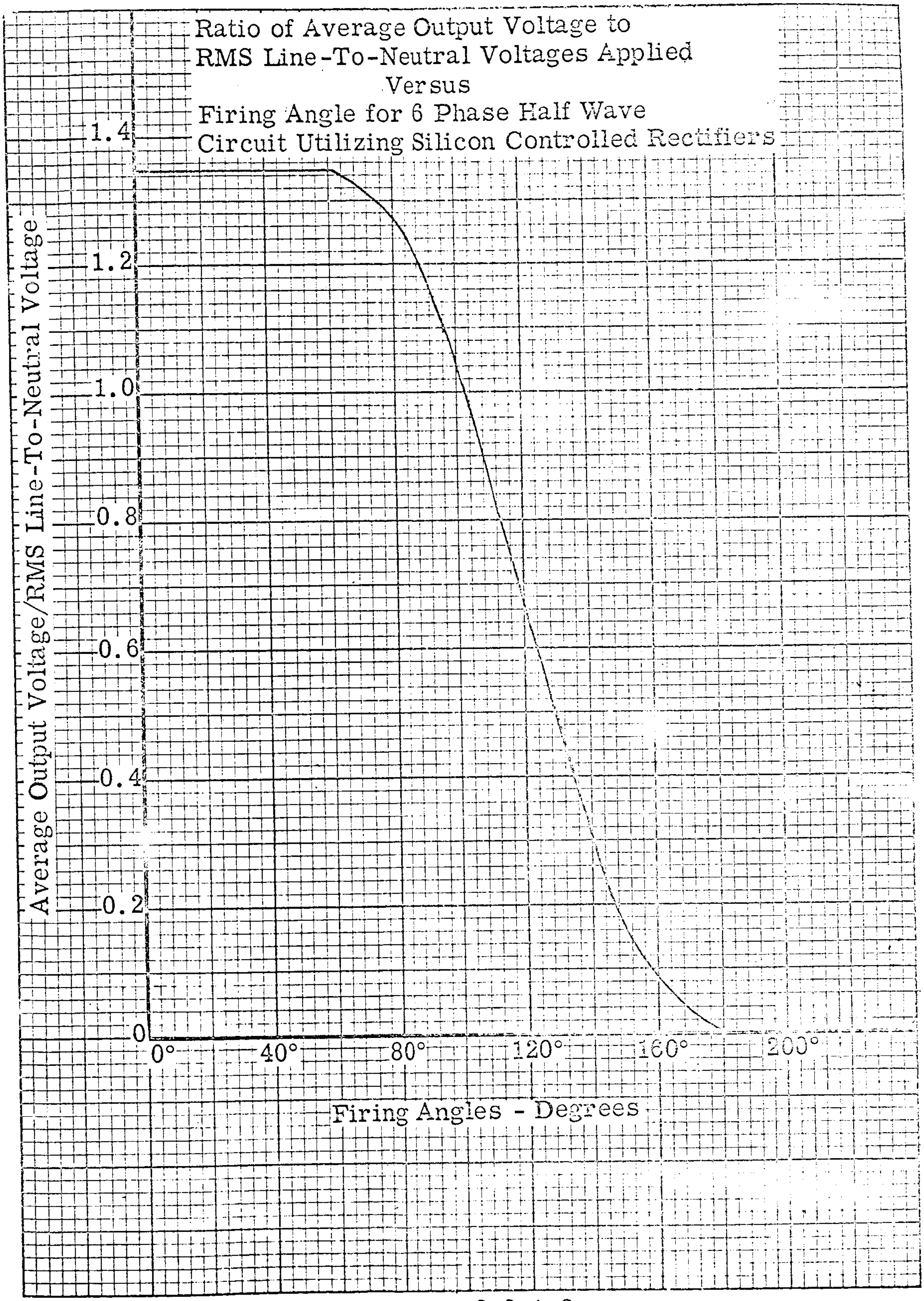

Ratio of Average Output Voltage to
RMS Line-To-Line Voltage Applied
Versus
Firing Angle For 3 Phase Full-Wave
Bridge Utilizing Silicon Controlled
Rectifiers
Average Output Voltage/RMS Line-To-Line Voltage
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
0°
40°
80°
120°
160°
200°
Firing Angle - Degrees

Figure 3. 2. 1-2



Ratio of Average Output Voltage to
RMS Line-To-Neutral Voltages Applied
Versus
Firing Angle for 6 Phase Half Wave
Circuit Utilizing Silicon Controlled Rectifiers
Average Output Voltage/RMS Line-To-Neutral Voltage
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
0°
40°
80°
120°
160°
200°
Firing Angles - Degrees

Figure 3. 2. 1-3

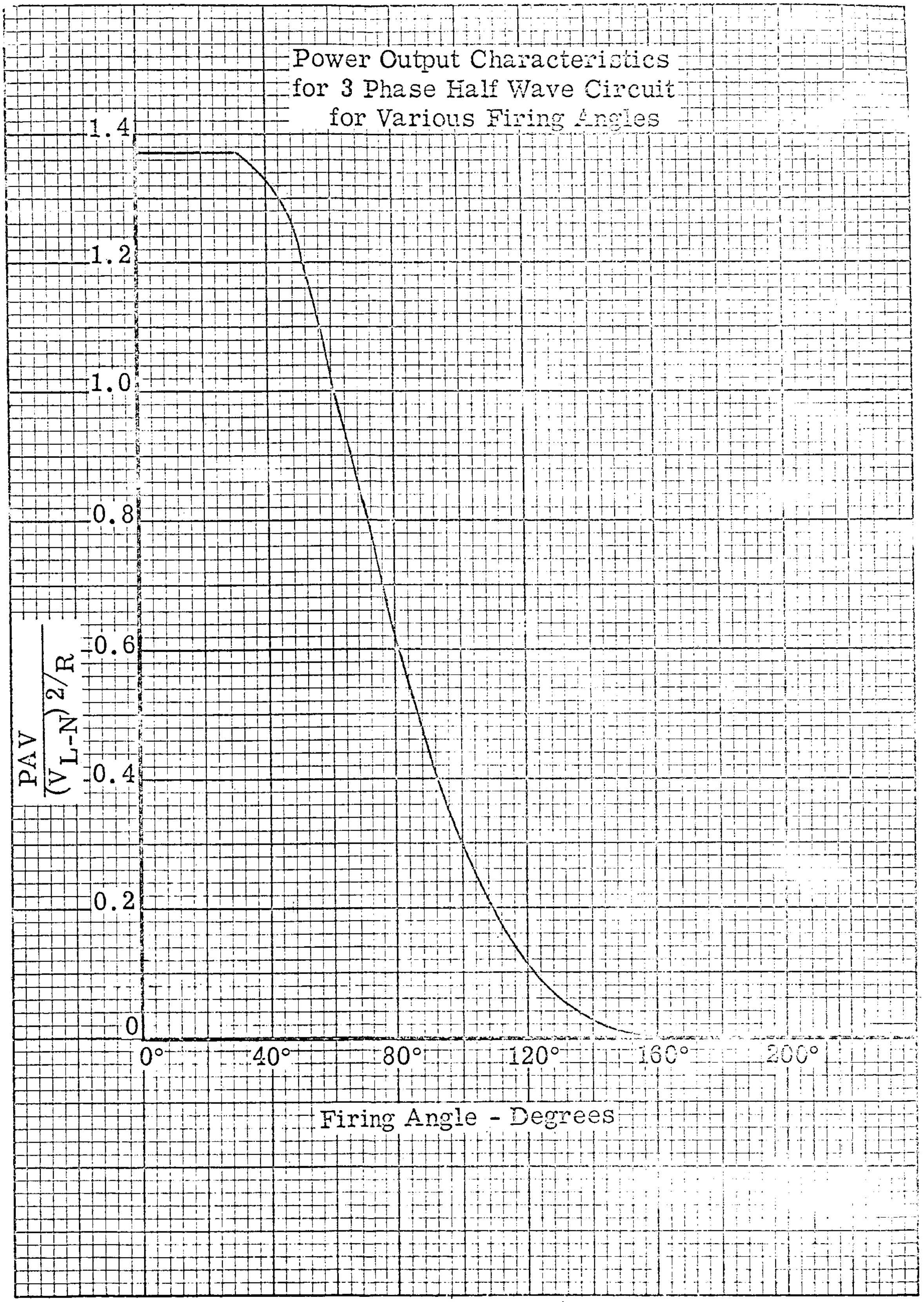

Power Output Characteristics
for 3 Phase Half Wave Circuit
for Various Firing Angles
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
$\frac{PAV}{(V_{L-N})^2/R}$
0°
40°
80°
120°
160°
200°
Firing Angle - Degrees

Figure 3. 2. 1-4

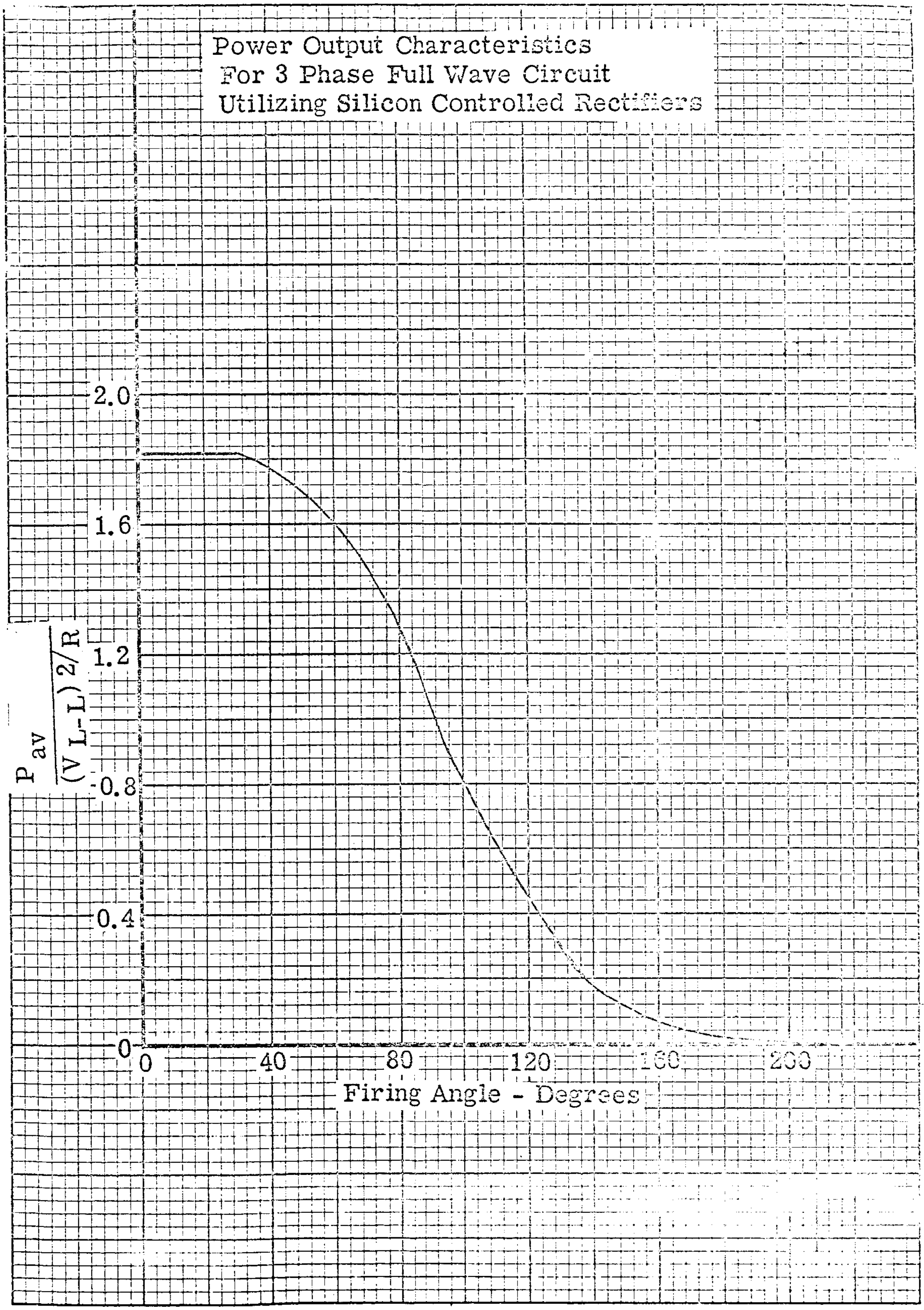
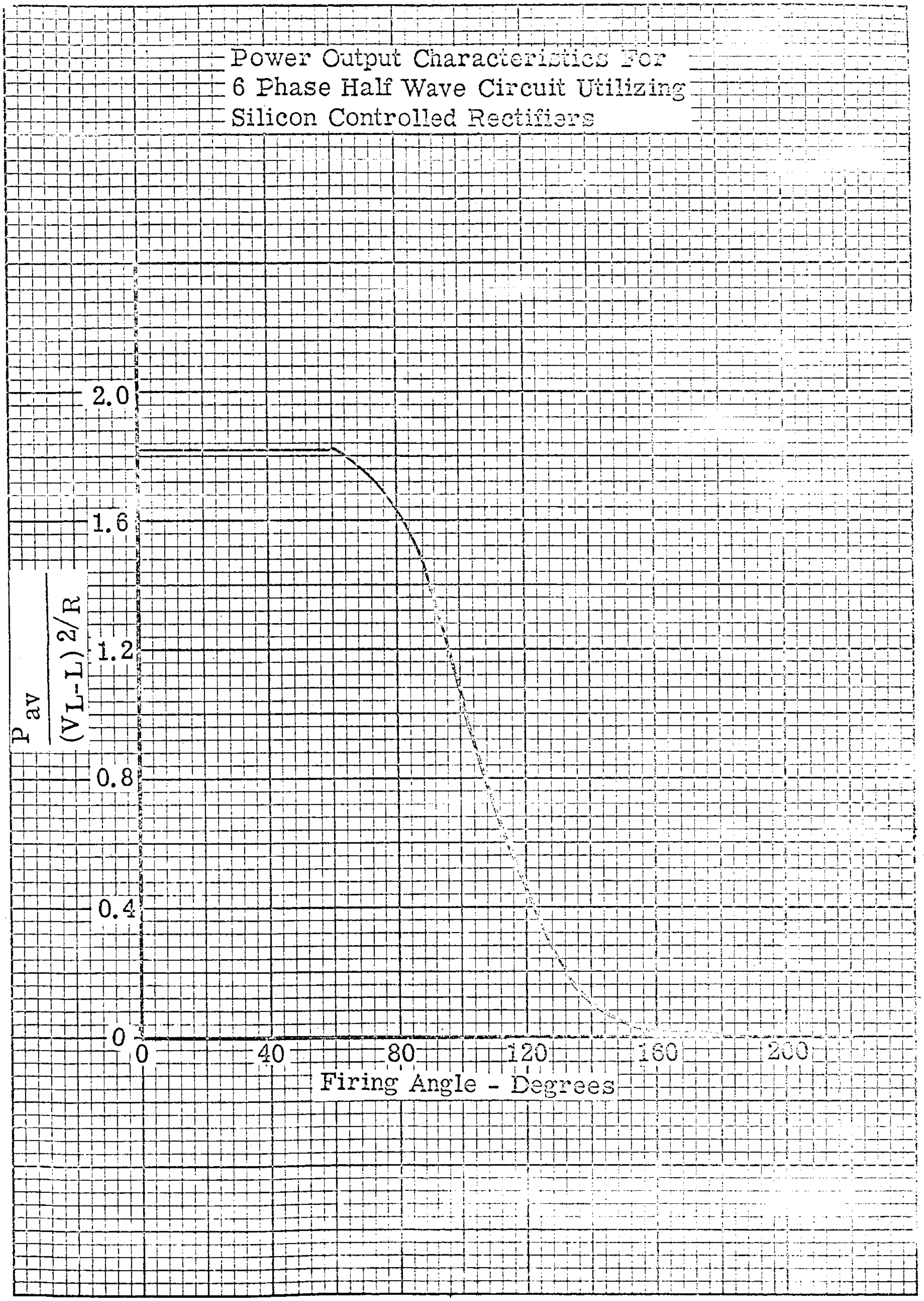

Power Output Characteristics
For 3 Phase Full Wave Circuit
Utilizing Silicon Controlled Rectifiers
$\frac{P_{av}}{(V_{L-L})^2/R}$
2.0
1.6
1.2
0.8
0.4
0
0
40
80
120
160
200
Firing Angle - Degrees

Figure 3. 2. 1-5



Power Output Characteristics For
6 Phase Half Wave Circuit Utilizing
Silicon Controlled Rectifiers
$\frac{P_{av}}{(V_{L-L})^2/R}$
2.0
1.6
1.2
0.8
0.4
0
0
40
80
120
160
200
Firing Angle - Degrees

Figure 3.2.1-6

25 percent. Also, calculations in all cases were based upon a coolant temperature of 50°C and transformer power losses and weights were based upon internal temperature rise of 300°C. Switching losses of the rectifiers have been neglected since they are usually a small percentage of the conduction losses. A five-megawatt generator (Design B, Table 3.2.1-1) was selected as the machine to be controlled as a basis for comparison of the three types of circuits. Table 3.2.1-2 summarizes the results. The total weight is the packaged weight of the exciter-regulator including coolant weight.

TABLE 3.2.1-2

Comparison of Weight and Power Loss of Three Different Power Stage Configuration for Exciter-Regulators Utilizing Silicon Controlled Rectifier Power Stage.

Circuit	Total Weight Lbs.	Total Power Loss Watts
Three-Phase Half-Wave	27.0	428
Three-Phase Full-Wave	20.25	295
Six-Phase Half-Wave	34.5	470

The table shows that the three-phase, full-wave circuit is the best from both weight and power loss standpoints. Therefore, this circuit will be used for all the other calculations.

Preamplifier

A three-phase, half-wave magnetic amplifier was selected for control of the silicon controlled rectifiers in the power stage. The proper phase relationship between the power stage supply voltage and gate signal to the silicon controlled rectifiers can be easily obtained with this configuration.

Parametric Data

Table 3.2.1-3 summarizes the packaged weight and total power losses for exciter-regulators for one, five and ten-megawatt generators of Table 3.2.1-1. The calculations were made for the generator operating at 1.0 per unit voltage and 1.0 per unit current output. There is essentially no weight or efficiency penalty on the exciter-regulator for generator output changes to 0.8 per unit voltage with 1.0 per unit current output and 1.0 per unit voltage with 0.8 per unit current output, so Table 3.2.1-3 also is valid for this requirement. An additional control circuit will, however, be required to supply a signal to the exciter-regulator that is proportional to load power for proper excitation control whenever variations in voltage output are required.

TABLE 3.2.1-3

Packaged Weight and Power Loss of Exciter-Regulators for 1, 5 and 10 Megawatt Generators at 1.0 Per Unit Voltage and Current.

Generator Design	Exciter-Regulator Weight - Lbs.	Exciter-Regulator Power Loss - Watts
A (1 MW)	18.2	252
B (5 MW)	20.25	295
C (10 MW)	22.1	341

The exciter-regulator designs shown in Table 3.2.1-4 are for control of one, five, and ten-megawatt generators when the generators are operating at 1.0 per unit voltage with 0.5 per unit current output and 0.5 per unit voltage with 1.0 per unit current output. Because the exciter-regulator must be designed for the most severe operating condition, (1.0 per unit voltage with 0.5 per unit current output from the generator), the weight is determined by this condition. The power loss is included at the 0.5 per unit voltage with 1.0 per unit current output for the circuit comparisons. Also included in Table 3.2.1-4 are the percentage increase in weight and power loss for these exciter-regulator designs as compared to the designs shown in Table 3.2.1-3 for the corresponding generator rating. This shows the penalty entailed by designing for generator voltage and current variations of 0.5 per unit.

TABLE 3.2.1-4

Packaged Weight and Total Power Loss of Exciter-Regulators for 1, 5, and 10 Megawatt Generators at 1.0 Per Unit Generator Voltage with 0.5 Per Unit Current and 1.0 Per Unit Generator Voltage with 0.5 Per Unit Current.

Generator Design	Ex.-Reg. Wt.-Lbs.	% Wt. Increase over Table 3.2.1-3 Design	Ex.-Reg. Power Loss Watts 1.0 p.u.V 0.5 p.u.I	0.5 p.u.V 1.0 p.u.I	% Power Loss Increase Over Table 3.2.1-3 Design
A (1 MW)	19.5	7.15%	314	182	24.6%
B (5 MW)	23.1	14.1 %	349	207	18.3%
C (10 MW)	26.6	20.4 %	413	223	21.1%

Several exciter-regulator designs were considered for the requirement of 0.1 per unit generator voltage with 1.0 per unit current output and 1.0 per unit generator voltage with 0.1 per unit current output. The ten-megawatt generator (Design C, Table 3.2.1-1) was selected for these calculations, but would have only one-megawatt power output capability for the above conditions. Since excitation power is being taken from the generator output, at 0.1 per unit voltage the voltage available to supply excitation is below the amount required by the generator if a three-phase, full-wave power stage is used with three silicon controlled rectifiers and three silicon rectifiers. Therefore, calculations were made for series and parallel combinations of rectifiers in the power stage to obtain enough excitation power. This proved infeasible for two reasons; (1) the firing angle approached 180 degrees when the generator output voltage was at 1.0 per unit and (2) the maximum power output capability of the exciter regulator was so high at 1.0 per unit voltage that it exceeded the allowable generator field power dissipation capabilities. A boost-current-transformer, exciter-regulator combination was considered with the current transformer supplying one generator field and the exciter-regulator supplying a second generator field and acting as a trimmer. This proved infeasible because the exciter-regulator output capability was marginal at 0.1 per unit voltage and also because of reason (2) cited above. The best method appears to be a tapped power transformer and tap changer for the exciter-regulator. This method will keep the voltage to the power and control stages fairly constant as the generator output voltage is varied. The weight and power loss for this type exciter-regulator is comparable to the exciter-regulator for the one megawatt generator shown in Table 3.2.1-4.

Figures 3.2.1-7, 8, and 9 show respectively, exciter-regulator weight, efficiency, and volume as a function of generator rating. Curve 1, in all three figures, applies to the generator when it operates at its rated point. (Curve 1 is also valid for 0.8 to 1.0 per unit generator voltage and current variations.) Curve 2, in all three figures, applies to the generator when it is operating at 1.0 per unit generator voltage and 0.4 per unit current. The weight and volume also apply for 0.5 per unit voltage and 1.0 per unit current, but the curve for exciter-regulator efficiency at this operating point has not been included. As can be seen on the curves, a penalty must be paid in exciter-regulator weight, efficiency and volume when variations of more than 0.2 per unit voltage and/or current are required.

In summary, an exciter-regulator with a three-phase, full-wave power stage utilizing three silicon controlled rectifiers and three silicon rectifiers with a magnetic-amplifier, gate-control circuit is the best design to fulfill the requirements imposed in this study program.

3.2.1.2 Magnetic-Amplifier, Silicon-Diode Exciter-Regulator Power Stage

The static exciter-voltage regulators considered here utilize saturable reactors and silicon rectifiers in the power stage, because a saturable reactor can be connected in series with a rectifying device to obtain a self-saturating magnetic amplifier and thus control the power output of the regulator. Any of the rectifier power circuits considered in section 3.2.1 may be used with this control method.

A sample calculation was made to compare the weights and efficiencies of the three-phase, half-wave magnetic amplifier and the three-phase full-wave magnetic amplifier power stages. The results showed that the three-phase half-wave power stage was lighter by 11.7 percent but its efficiency was

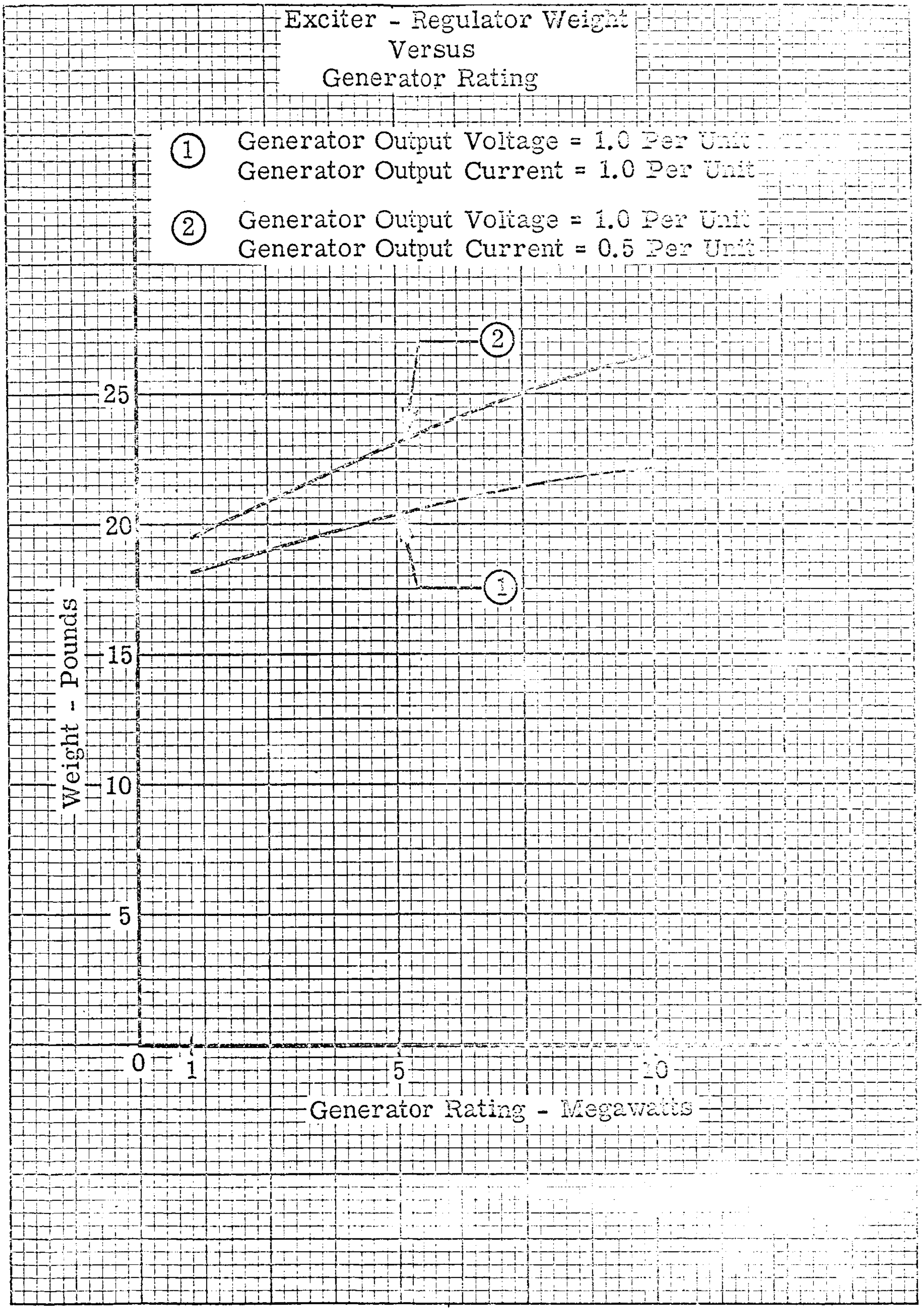

Exciter - Regulator Weight
Versus
Generator Rating
(1) Generator Output Voltage = 1.0 Per Unit
Generator Output Current = 1.0 Per Unit
(2) Generator Output Voltage = 1.0 Per Unit
Generator Output Current = 0.5 Per Unit
(2)
(1)
Weight - Pounds
25
20
15
10
5
0
1
5
10
Generator Rating - Megawatts

Figure 3. 2. 1-7

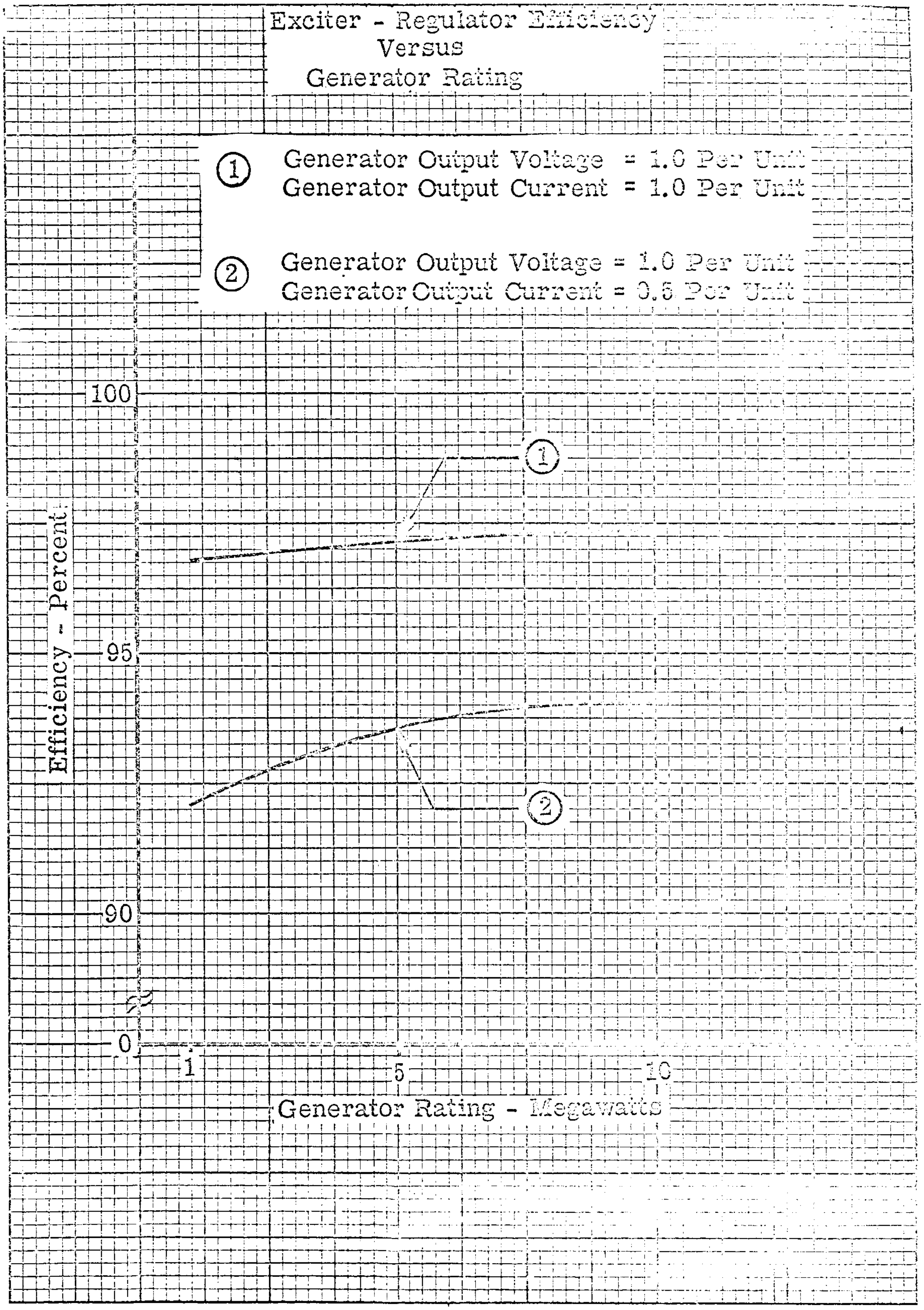
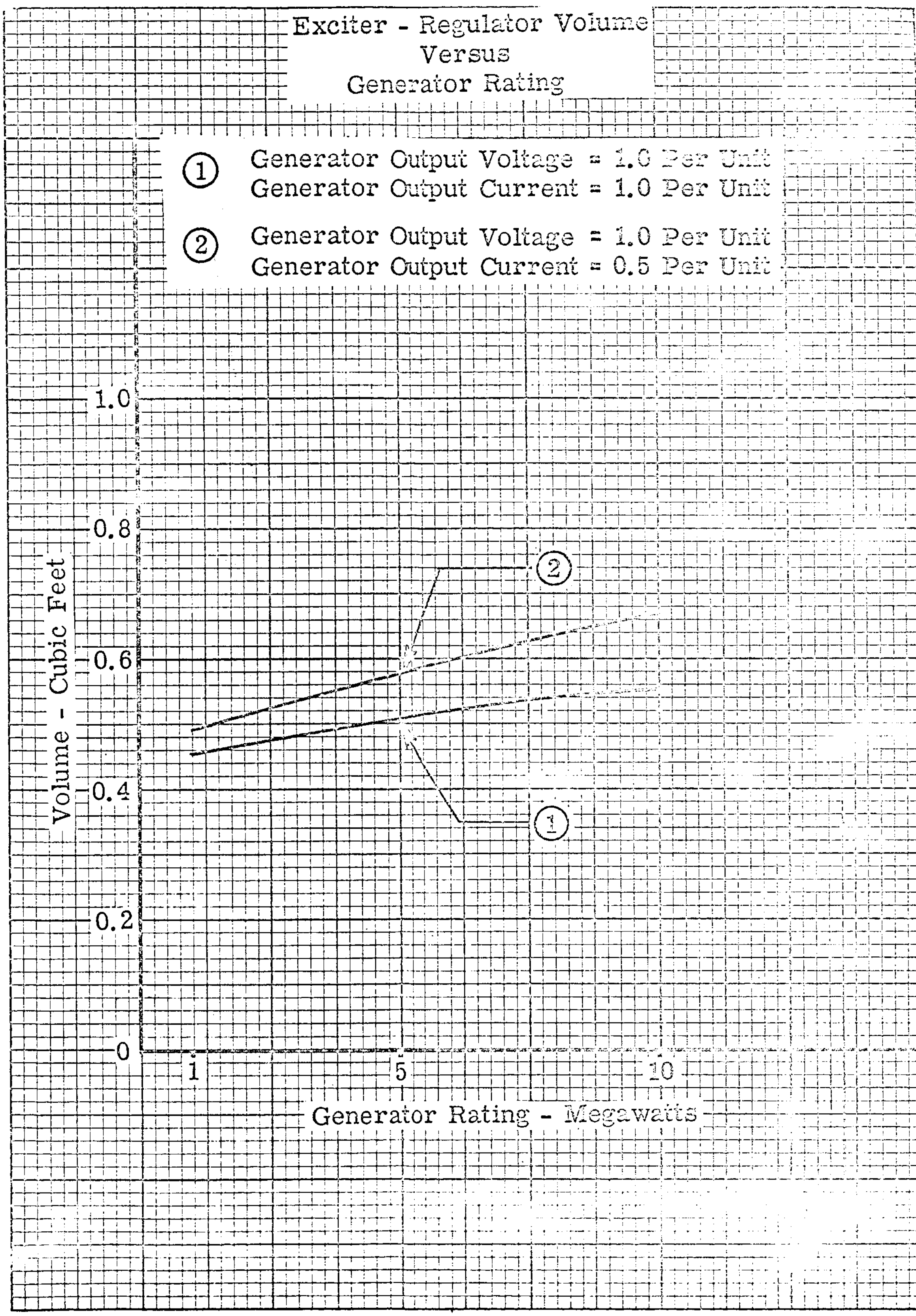

Exciter - Regulator Efficiency
Versus
Generator Rating
① Generator Output Voltage = 1.0 Per Unit
Generator Output Current = 1.0 Per Unit
② Generator Output Voltage = 1.0 Per Unit
Generator Output Current = 0.5 Per Unit
100
95
90
0
1
5
10
Efficiency - Percent
Generator Rating - Megawatts
1
2

Figure 3. 2. 1-8



Exciter - Regulator Volume
Versus
Generator Rating
① Generator Output Voltage = 1.0 Per Unit
Generator Output Current = 1.0 Per Unit
② Generator Output Voltage = 1.0 Per Unit
Generator Output Current = 0.5 Per Unit
Volume - Cubic Feet
1.0
0.8
0.6
0.4
0.2
0
1
5
10
Generator Rating - Megawatts

Figure 3. 2. 1-9

lower by 13.3 percent. The full-wave circuit was chosen, however, because it permits operation of the rectifiers at lower currents and higher voltage, thus allowing the generator field resistance to be increased. The increased generator field resistance is important because it will swamp out the effect of lead resistance.

The maximum operating junction temperature for high power silicon rectifiers is 190°C.[1] This will allow operation of exciter-regulators utilizing these devices in the power stage at higher temperatures than the exciter-regulators utilizing silicon controlled rectifiers. Therefore, the exciter-regulator designs in this section will be based upon an average coolant temperature of 100°C.

Preamplifier

The preamplifier, as stated previously, receives an error signal from the error detector (sensing circuit), amplifies this signal, and furnishes the control signal to the power stage of the exciter-regulator. A three-phase half-wave magnetic amplifier has been selected to perform this function. This circuit is not as efficient as the three phase full wave magnetic amplifier but due to the low power requirements of the preamplifier this becomes relatively unimportant. The three-phase circuit gives consistent operation for any unbalance between phases of the generator output voltage due to an unbalanced load or unbalanced fault. If a single-phase magnetic amplifier were used, operation under an unbalanced load or unbalanced fault would

1. Reference section 3.2.2.2, Silicon Rectifiers, in the Space Electric Power Systems Study Progress Report - First Quarter.

depend upon the relationship of the faulted phase and the phase used for the preamplifier power supply.

Parametric Data

The parametric data for these exciter-regulators is based upon the following assumptions:

1. The normal steady-state peak-inverse voltage applied to the silicon rectifiers is half their maximum peak-inverse-voltage ratings.
2. The average temperature of the exciter-regulator coolant fluid is 100 degrees centigrade.
3. The maximum steady-state current of the silicon rectifiers is held low enough so the maximum junction temperature is derated by at least 25 percent.
4. The magnetic amplifier is designed and packaged to hold the temperature rise to 50°C maximum.
5. The power-transformer power loss and weight is based upon 180°C temperature rise.

Table 3.2.1-5 shows the packaged weight, packaged volume, and power loss for exciter-regulators for control of the generators of Table 3.2.1-1 when operating at 1.0 per unit voltage with 1.0 per unit current output. This exciter-regulator, like that in section 3.2.1.1, is suitable for control of the generators when they are operating at 0.8 per unit voltage with 1.0 per unit current output and a 1.0 per unit voltage with 0.8 per unit output. For a requirement of 0.2 per unit voltage and current swing at constant power output, an additional control circuit must be furnished to supply a signal to the exciter-regulator that is proportional to load power for proper excitation control.

TABLE 3.2.1-5

Packaged Weight, Packaged Volume, and Power Losses for Exciter-Regulators for 1, 5, and 10 Megawatt Generators Operating at 1.0 Per Unit Voltage and Current.

Generator Design	Exciter-Regulator		
	Weight-lbs.	Volume-ft^3	Power Loss-Watts
A (1 MW)	40.8	0.916	454
B (5 MW)	49.6	1.12	567
C (10 MW)	56	1.26	658

The requirement of generator operation at 0.5 per unit voltage with 1.0 per unit current output and 1.0 per unit voltage with 0.5 per unit current output imposes a penalty on the exciter-regulator. The regulator must be designed to have the capability of supplying the necessary excitation when the generator is operating at 0.5 per unit voltage. Since it is assumed that the power to the regulator is obtained from the generator bus voltage, when the load requirement is such that 1.0 per unit voltage output is required from the generator, the regulator has approximately twice the voltage output capability for the same conduction angle. Therefore, the conduction angle must be decreased because the regulator power output is higher than required by the generator. This results in higher rms currents per phase which requires a larger power transformer and power-stage magnetic amplifier and results in larger power losses in the regulator. Table 3.2.1-6 shows the exciter-regulator packaged weight, packaged volume, and power loss for generators operating at 1.0 per unit voltage with 0.5 per unit current out-put.

TABLE 3.2.1-6

Packaged Weight, Packaged Volume and Power Loss of Exciter-Regulator for 1, 5, and 10 Megawatt Generators Operating at 1.0 Per Unit Voltage with 0.5 Per Unit Current Output.

Generator Design	Exciter-Regulator		
	Weight-lbs.	Volume-ft^3	Power Loss-Watts
A (1 MW)	45.9	1.03	500
B (5 MW)	54.8	1.23	594
C (10 MW)	65.8	1.48	734

The curves shown in Figures 3.2.1-10, 11, and 12 show exciter-regulator packaged weight, packaged volume, and efficiency as a function of the generator rating. Curve 1, on each figure, represents the exciter-regulators that control generators operating at rated voltage and current. Curve 2 on each figure, is for exciter-regulators that control generators operating at 1.0 per unit voltage with 0.5 per unit current output. The weight and volume is also valid for the operating point of 0.5 per unit voltage with 1.0 per unit current output; the power losses, however, are lower. The efficiency curve for condition 2 is shown for the higher steady-state power loss.

Conclusions

A comparison of the parametric data for exciter-regulators utilizing magnetic amplifiers in the power stage with exciter-regulators using silicon-controlled rectifiers shows that the latter is more efficient and has smaller size and weight. The lower efficiency of the magnetic amplifier type is caused by the additional power loss in the power-stage magnetic amplifier and in the power transformer. Power transformer losses increase because of the higher voltage and current output required because of the voltage drop across the saturated reactance of the magnetic amplifier. The increased size and weight is due to the larger power transformer required and the power stage magnetic amplifier, which is an additional component not required in the exciter-regulator using silicon controlled rectifiers. A system analysis is necessary to determine if the 50°C increase in coolant temperature offsets the increase in size, weight and lower efficiency of exciter-regulator using magnetic amplifiers. Another consideration is the additional time delay introduced by the magnetic amplifier will usually make stabilization of the system more difficult and impose some penalty on system transient performance.

3.2.1.3 Magnetic-Amplifier, High-Temperature-Gas-Tube-Diode Exciter-Regulator.

<u>Power Stage</u>

For these static-exciter, voltage-regulator designs utilizing a magnetic amplifier with high temperature tubes in the power stage for control of 1, 5, and 10 megawatt generators, the three-phase, full-wave circuit was chosen for the reasons stated in section 3.2.1.2. The high-temperature gas tubes would permit operation up to ambient temperatures of 400°C.[1] However, the limitation imposed by the

1 Reference section 3.2.4, High-Temperature, Gas-Tube Diodes, in the Space Electric Power Systems Study Progress Report - First Quarter

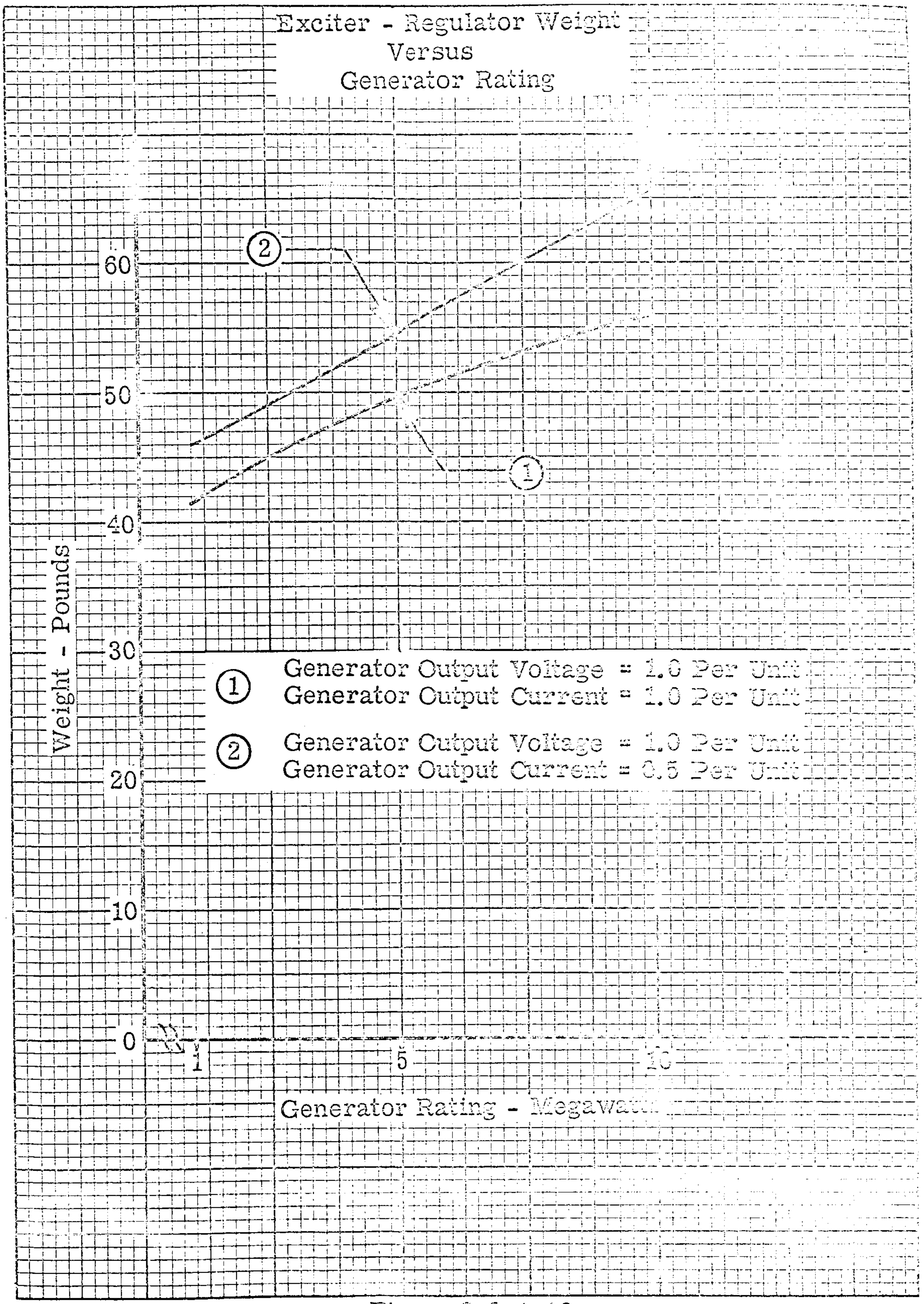


Figure 3. 2. 1-10

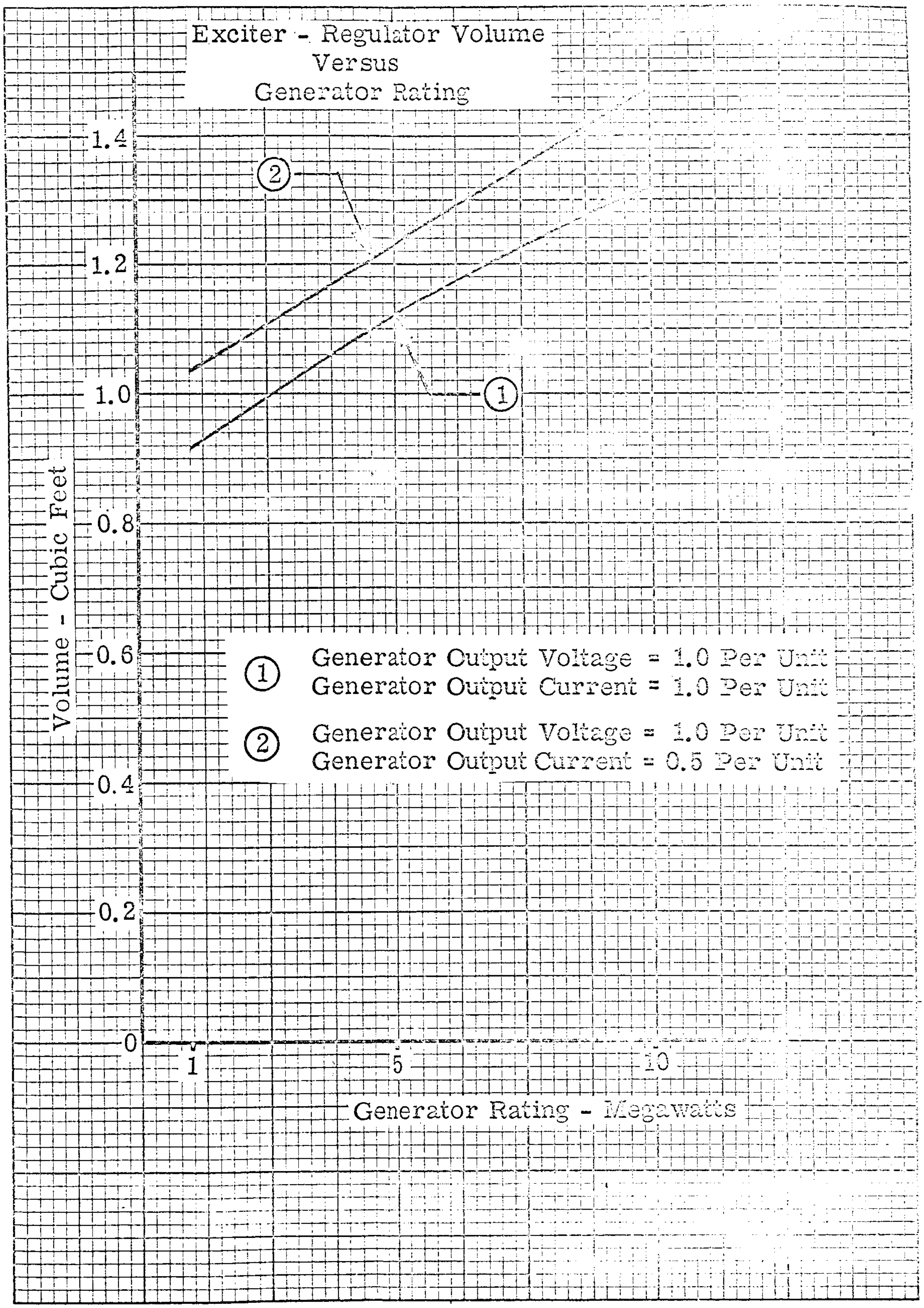


Figure 3. 2. 1-11

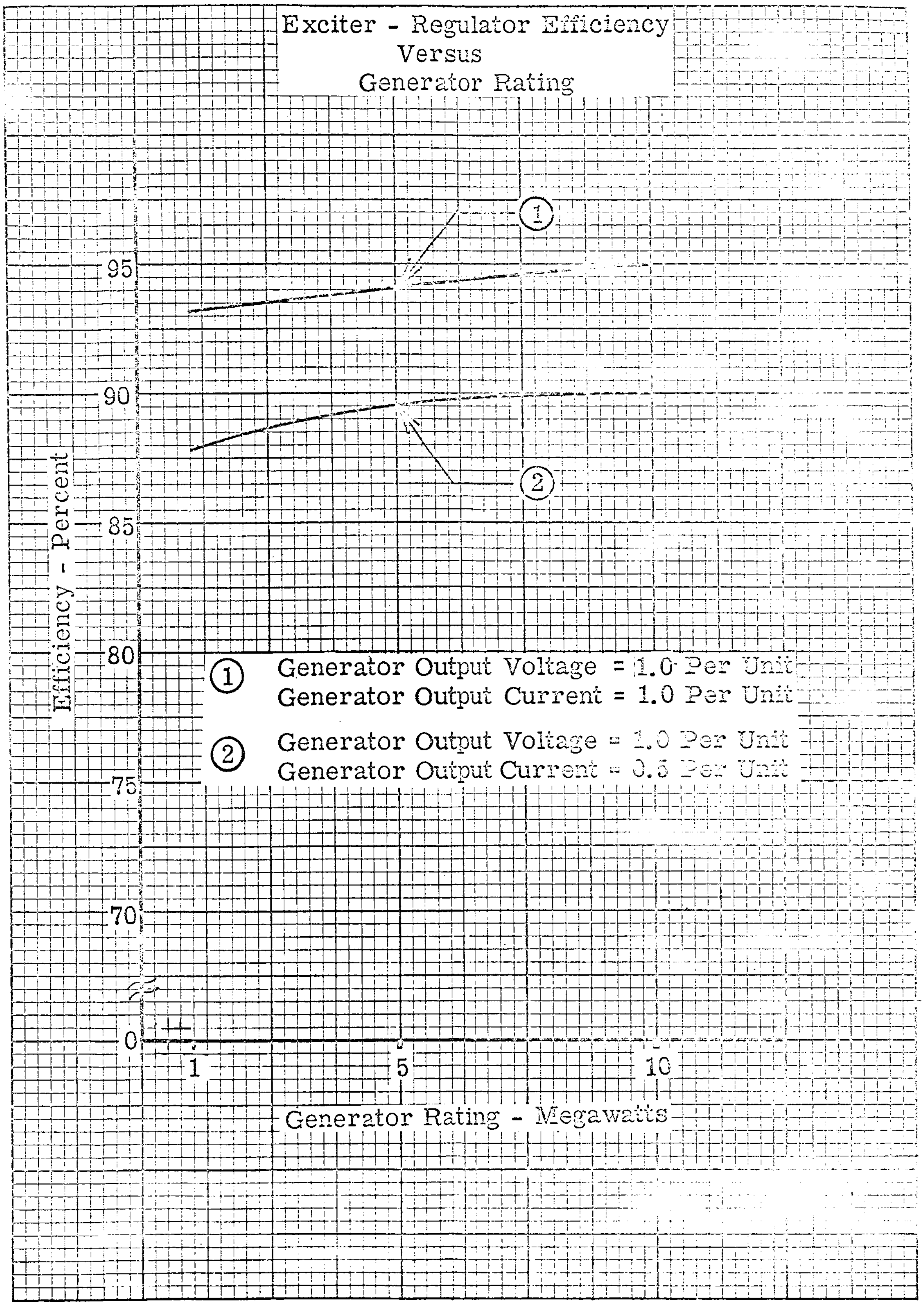


Figure 3. 2. 1-12

present state-of-the-art for magnetic amplifiers restricts the upper operating temperature to 180°C.[2] Because of this magnetic amplifier temperature limitation, it is assumed that the average coolant temperature is maintained at 180°C.

The use of gas-tube diodes in lieu of silicon rectifiers to attain higher temperature operation for the exciter-regulator results in higher power losses for two reasons: (1) higher tube forward voltage drop, (2) the tubes are the not cathode type and require filament power for direct heating of the cathodes. The filament power requirements (95 watts at 2.5 volts rms) exceed the tube forward conduction power losses and result in lower regulator efficiency.

The magnitude of the applied filament voltage is critical, since tube forward voltage drop is a function of filament voltage; therefore, the filament voltage must be held at the proper level to assure maximum reliability. Assuming the power supply voltage for the voltage regulator is taken from the generator terminals fluctuations in this voltage will affect the filament voltage; therefore, means of regulating this voltage such as a constant voltage transformer or voltage regulator glow tube will be required. A circuit to provide this function has not been determined and its effect has not been taken into account in the parametric data.

The section on High-Temperature, Gas-Tube Diodes (see footnote 1) states that the present gas tube with a 10 ampere average forward current rating is available

[2] Reference section 3.2.2.1, High-Temperature Magnetic Amplifiers, in the Space Electric Power Systems Study Progress Report - First Quarter

in a peak inverse voltage rating of 200 volts. Data for the 10 ampere tube "scaled up" to 10,000 volts PIV is also given. Because a 10 ampere, 1500 volts PIV tube is adequate for the amount of excitation power required (a safety factor of 2 on PIV) is is assumed that a tube with a peak-inverse-voltage rating of 1500 volts can be developed with parametric data and physical characteristics the same as for the 10 ampere, 10,000 volt unit, except the height. For purposes of estimating the packaged regulator volume, the height of the 1500 volts PIV tube is assumed to be 4.8 inches.

Preamplifier

A three-phase, half-wave magnetic amplifier was selected as the preamplifier for this exciter-regulator as in the two previous cases. The choice of the coolant temperature of 180°C has an advantage in that the rectifying elements required for the preamplifier and also the sensing circuit can be silicon diodes instead of gas tubes. This is made possible by a relatively new silicon glass diode manufactured by Unitrode Transistor Products, Inc., Waltham, Massachusetts. Their published data sheets specify an ambient operating temperature range of -100°C to +250°C in current ratings up to 3 amperes at +25°C. With derating at increased ambient temperatures, this device has sufficient current capacity for this application. By using this device, instead of gas-tube diodes, considerable savings in size, weight and power loss can be realized. Reduction in power loss is realized because the silicon diode required no filament power and has lower power dissipation during conduction.

Parametric Data

Table 3.2.1-7 shows the packaged weight, packaged volume, and power loss for exciter-regulators for control of the generator designs of Table 3.2.1-1. The data shown in Table 3.2.1-7 is for exciter-regulators that control generators operating at 1.0 per unit voltage with 1.0 per unit current output. The data is also valid for generators operating over a 0.8 to 1.0 per unit voltage and current range.

TABLE 3.2.1-7

Packaged Weight, Packaged Volume, and Power Losses for Exciter-Regulators for 1, 5, and 10 Megawatt Generators Operating at 1.0 Per Unit Voltage with 1.0 Per Unit Current Output.

Generator Design	Exciter-Regulator		
	Weight-lbs.	Volume-ft^3	Power Loss-Watts
A (1 MW)	65	1.37	1384
B (5 MW)	80.5	1.68	1578
C (10 MW)	91	1.89	1708

Table 3.2.1-8 shows the same exciter-regulator data as Table 3.2.1-7 except the generator operating point is 1.0 per unit voltage and 0.5 per unit current. These exciter-regulators are also capable of controlling the generator when operating at 0.5 per unit voltage and 1.0 per unit current. Data is given for the 1.0 per voltage 0.5 per current condition because this is the most severe operating condition.

It should be noted again that the generator voltage variations, made necessary by the constant power output requirements, will cause problems in maintaining constant filament supply voltage and the circuit required to regulate this voltage has not been taken into account in the exciter-regulator package and power losses.

TABLE 3.2.1-8

Packaged Weight, Packaged Volume, and Power Losses for Exciter-Regulators for Generators Operating at 1.0 Per Unit Voltage with 0.5 Per Unit Current Output.

Generator Design	Exciter-Regulator		
	Weight-lbs.	Volume-ft^3	Power Loss-Watts
A (1MW)	72	1.51	1323
B (5 MW)	84.6	1.76	1554
C (10 MW)	105	2.17	1773

A graphical representation of exciter-regulator packaged weight, packaged volume, and efficiency is shown in Figures 3.2.1-13, 14, and 15. Curve 1 on each figure is for exciter-regulators that control generators operating at 1.0 per unit voltage and current. Curve 2, on each figure, is for exciter-regulators that control generators operating at 1.0 per unit voltage with 0.5 per unit current output.

Conclusions

The larger size of high temperature components results in a larger package for this type of exciter-regulator than for the previous two types. The efficiency is lower because of the filament power required by the high temperature tubes and higher tube forward voltage drop. Here again, a system analysis will be required to determine if the higher allowable coolant temperature is worth the additional cost in size and weight.

A development program which culminated in a magnetic amplifier which had relatively high power handling capabilities in the temperature range from

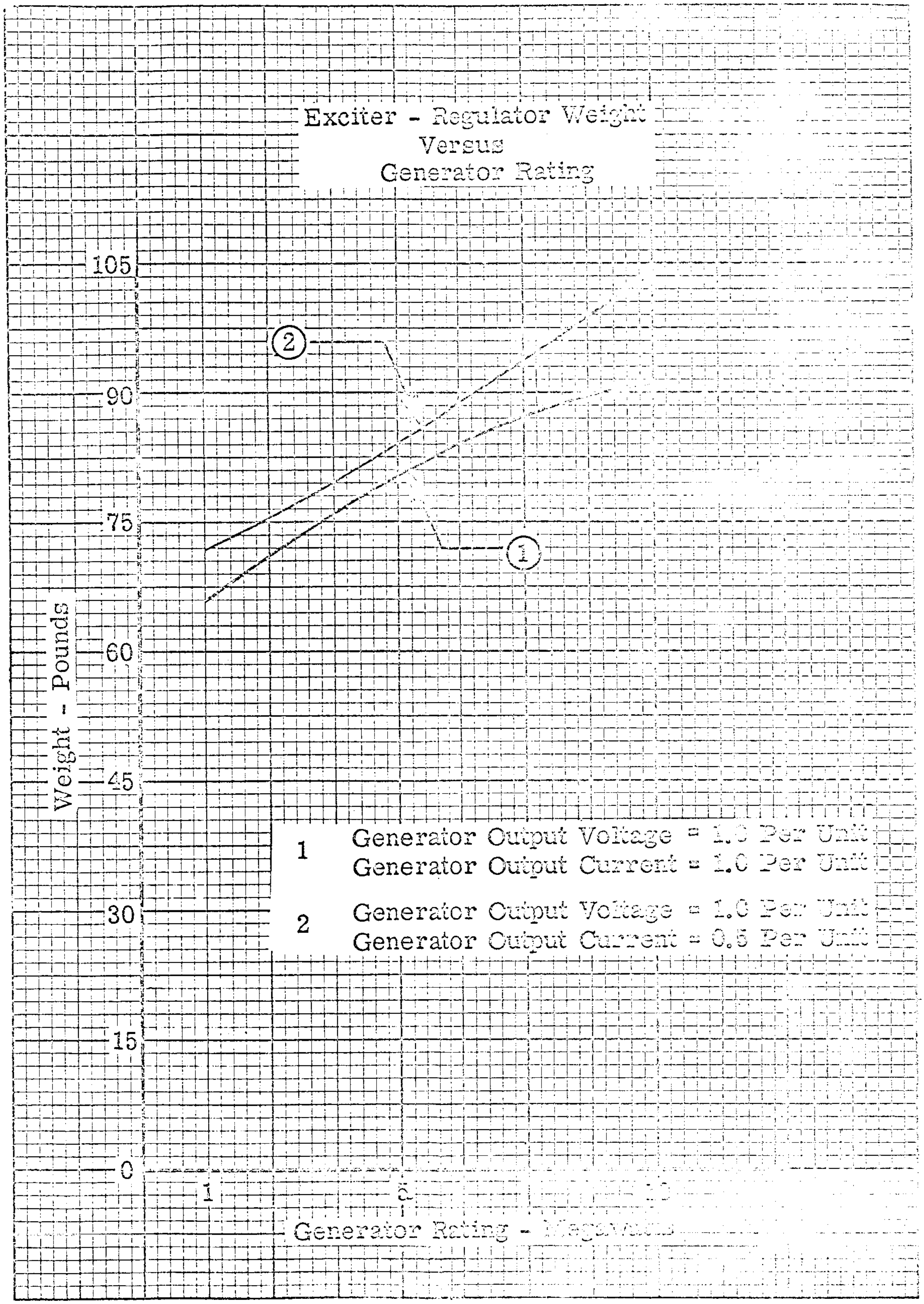


Figure 3. 2. 1-13

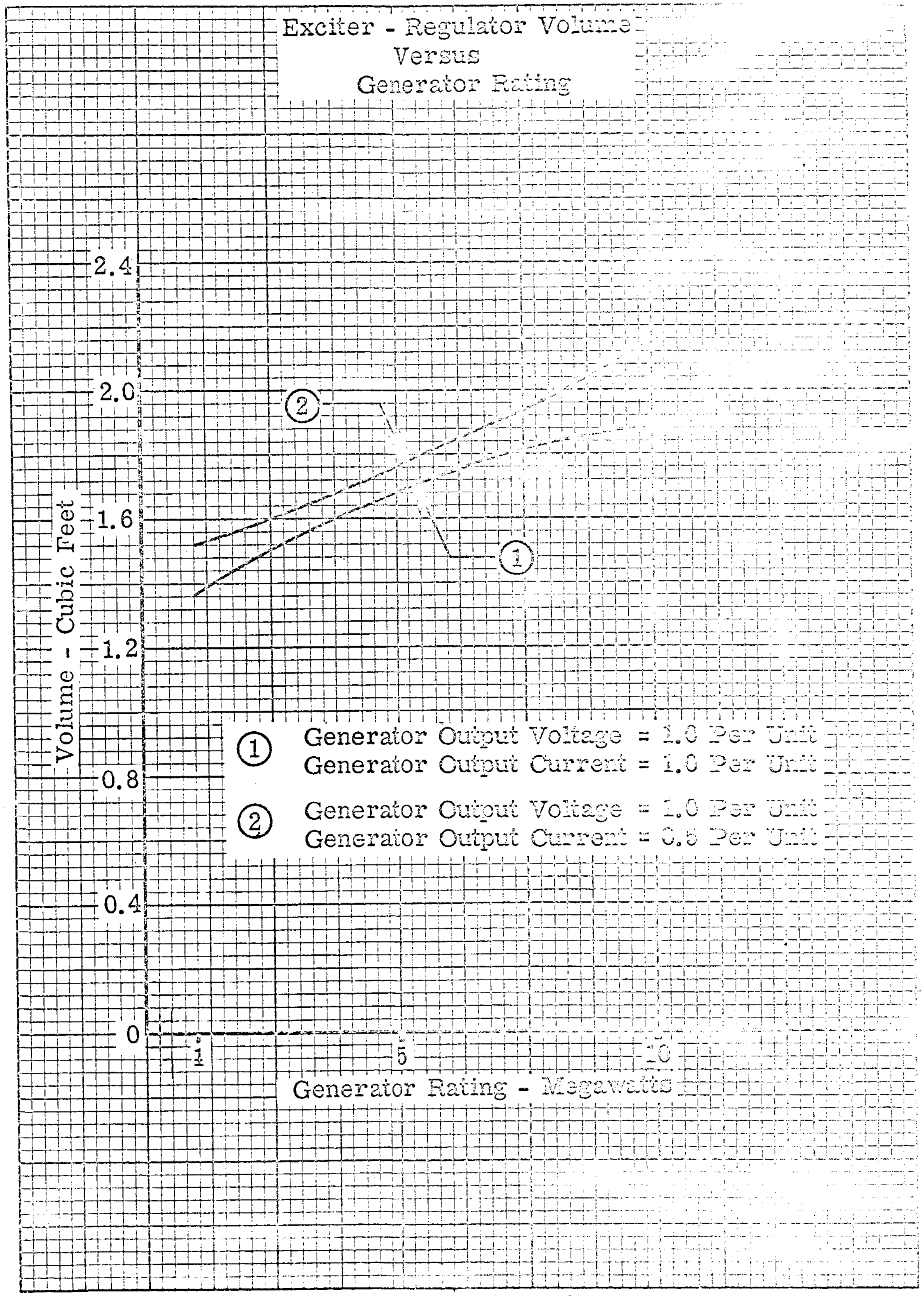


Figure 3.2.1-14

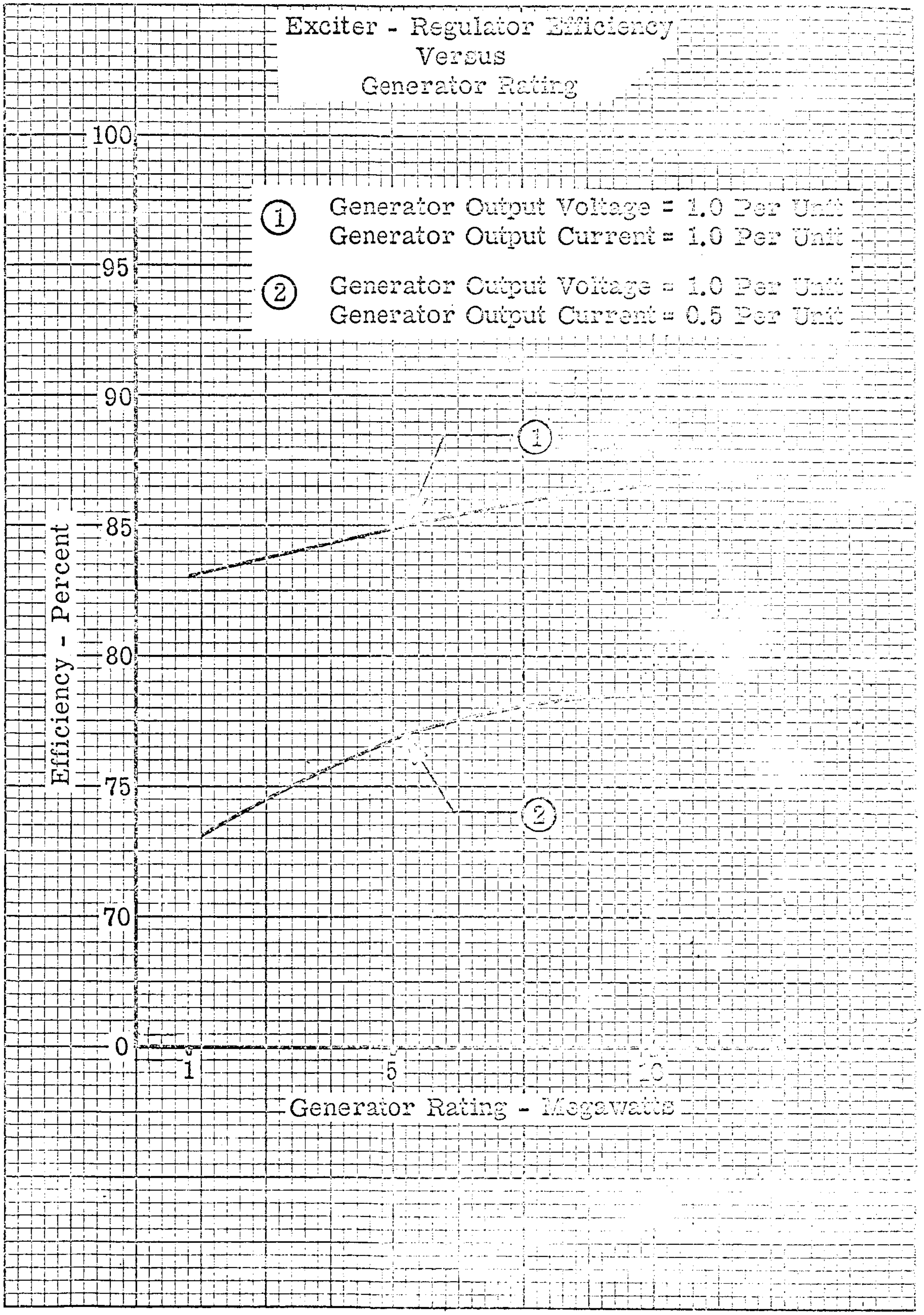


Figure 3. 2. 1-15

350°C to 400°C would allow design of an exciter-regulator capable of operation at coolant fluid temperatures in 300°C to 350°C range. Advancement in the state-of-the-art for materials and also manufacturing techniques would be required to obtain this operating temperature range (reference High Temperature Magnetic Amplifiers, footnote 2).

Another possible approach to high temperature operation would be development of a high temperature thyratron. Possibly the preamplifier could utilize high temperature gas triodes for thyratron control. High temperature gas triodes are now available but high temperature thyratrons are not.

The above development programs are cited as additional approaches extending the allowable operating temperature for exciter-regulators.

Development work has been preformed on a voltage regulator capable of operation at temperatures in the 315°C range on the Hotelec program. This regulator utilizes high-temperature, gas tubes and magnetic amplifiers. However, the steady power output capability of the regulator is in the 200 watt range which is far below the excitation requirements for this application.

3.2.1.4 Magnetic-Amplifier, High-Temperature-Semiconductor Exciter-Regulator.

High temperature diodes presently available are fabricated of gallium arsenide.[1] The maximum peak-inverse-voltage rating available is 55 volts and the maximum forward current rating is 250 milliamperes. The power handling capabilities

1 Reference section 3.2.2.5, High Temperature Semiconductors in the Space Electric Power Systems Study Progress Report - First Quarter

of this device make it unacceptable for high temperature, high-power exciter-regulators at the present time. The present state-of-the-art of high-temperature magnetic amplifiers capable of providing high-power output, limits the allowable operating temperature to approximately +180°C.[2] Advances in the state-of-the-art (see footnote 1 and 2) may prove these designs feasible at some later date, but for the present these designs will be deferred.

2 Reference section 3.2.2.1, High Temperature Magnetic Amplifiers, in the Space and Electric Power Systems Progress Report - First Quarter.

3.2.2 Switch Gear

The switch gear necessary to accomplish the various system functions has been described in the First Quarterly Report. The following is a summary of the three types of switch gear needed.

1. Line Circuit-Breaker

   A line circuit-breaker is required on the generator output to provide a means of disconnecting the load during system startup, system shut-down, and permanent fault removal. In addition it provides the function of interrupting and reclosing, when directed by suitable control intelligence, as in the case of temporary flash-overs of the propulsion machinery.

2. Bank Switch

   The bank switch is required for 100-percent step changes in bus voltage. This device is used in conjunction with isolated-transformer-secondary sections and their associated rectifier-banks to provide these large variations in bus voltage.

3. Tap-Changer

   The tap-changer is required for less than 100-percent step changes in bus voltage. Its function is to place the generator output voltage on various taps of the transformer primary to effect a change in the transformer turns-ratio.

The general approach toward parametrically evaluating the above switch gear is:

1. Dielectric Properties;

The dielectric properties of a vacuum are much more favorable than that of any of the solids or gaseous media. Some of the literature states dielectric strengths of 10^6 volts-per-centimeter in a vacuum. For this reason, it was decided to utilize a non-hermetic-sealed approach on all switch gear.

2. Interruption in vacuum;

Power interruption in a vacuum environment has been found to be very superior to either liquid or gaseous media. In the case of liquid or gaseous media, the mean-free path of particles within the interrupting gap is very short; hence, the mechanism of avalance collisions and the resulting ionization is a very predominate factor in successful power interruption. For successful power interruption, then, a conventional means of de-ionizing these media must be incorporated. In the case of the vacuum environment, the mean-free path of particles within the gap is much longer than the gap itself, hence, the condition of avalance collision to produce ionization is virtually non-existant. For this reason, the parametric approach for the above equipment was again directed toward utilizing the vacuum environment to gain the superior interrupting ability and again to avoid hermetic sealed enclosures.

3. Steady State Losses;

There are two prime sources of steady state losses in the above switch-gear. These are the I^2R loss at the contact faces and the I^2R losses throughout the interconnecting bus-work in the switch gear itself. Rated current levels for the various switch gear ranges from 25 amperes input on an 8 bank switch to 6,667 amperes line current on the circuit breaker and tap changer.

4. Contact configuration;

The basic configuration of the knife-type contact is in figure 3.2.2-1. This configuration was chosen because; (1) the configuration inherently provides two parallel paths for the load current; (2) the physical width of the contact can be increased to provide a line contact rather than a point contact; (3) flexibility of the female portion of the contact can be achieved by spring-loaded butt-edges, thereby avoiding the need for flexible bus work; (4) operation of this type contact can be accomplished by entering the male section from either side or, by suitable design, from the front. This flexibility of engagement was used primarily in the tap changer and bank switch equipment.

5. Cold Welding in vacuum;

The most severe problem, from a feasibility standpoint for the switch gear, is cold-welding contact surfaces in a vacuum environment. This is recognized as a very serious problem and one that must be solved before detailed designs of mechanical switch-gear for vacuum use can be completed. The parametric estimates of all the above switch-gear was prepared on the assumption that the cold-welding problem can be resolved and feasible solutions achieved. It is anticipated that much experimental work must be done, in order to select those metals, alloys and/or mixtures which will not be vulnerable to cold-welding and still

LINE CIRCUIT BREAKER
CONTACT CONFIGURATION

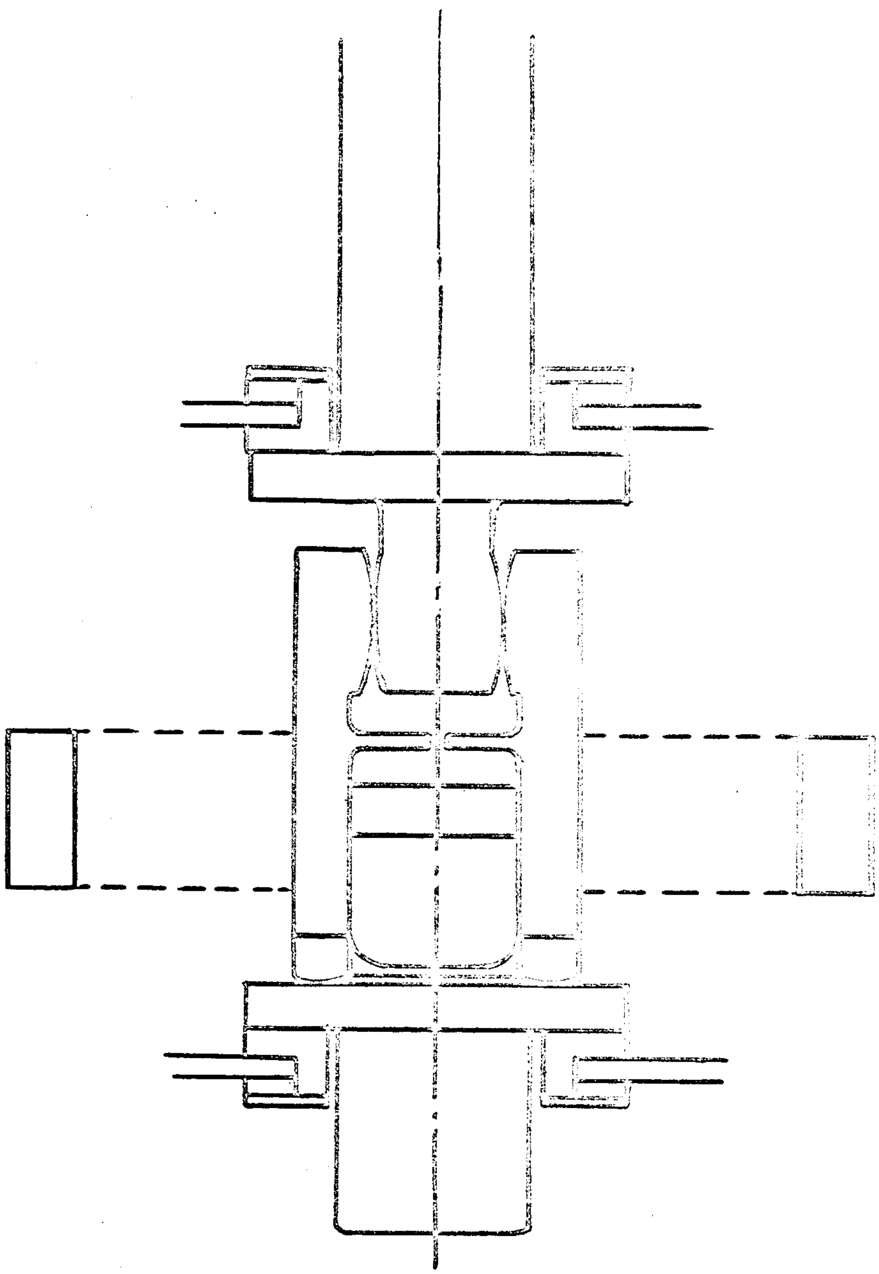


Figure 3. 2. 2-1

have feasible electrical characteristics, before firm switch gear designs can be achieved.

An alternate approach to avoid cold-welding is to seal the equipment and to provide an artificial environment. This could utilize several atmospheres of internal pressure for increased dielectric and interrupting capabilities. Larger and heavier equipment would, however, result along with the additional problem of seal reliability. The sealed approach is not considered in this study.

6. Cooling;

The bank switch and tap changer will be cooled by passing coolant fluid through coils or tubes attached to the stationary outer drum. Heat generated by bus and contact losses at the outer drum will pass to the coils by conduction. Radiation will be utilized to transfer heat losses from the inner drum to the outer drum. The line circuit breaker will be cooled by coolant tubes or a cold-plate built into the structure of the unit.

Curves are presented showing weight, volume, and losses with coolant average temperatures of 100°C, 300°C, and 500°C. Coolants and allowable temperature rises are as follows:

Coolant Average Temperature	Coolant Fluid	Temperature Rise
100°C	Monoisopropyl biphenyl	20°C
300°C	OS-124 or eutectic NaK	15°C
500°C	OS-124 or eutectic NaK	10°C

The above characteristics of the coolant fluids are based on the analysis presented in the First Quarterly Report. (See Figures 3.2.4-2 through 3.2.4-4 in the First Quarterly Report.)

3.2.2.1 Line Circuit Breaker

The line circuit breaker is fundamentally a three-pole single-throw device with an actuating mechanism capable of remote operation. This type of circuit breaker was chosen based on the assumption that the physical location of the circuit breaker in an actual space vehicle system, and also the mode of electrical system operation, would not be compatible with a manually operated circuit breaker.

Figure 3.2.2-2 is a schematic diagram of the line circuit breaker. The breaker will open or close the three-phase lines when the trip or close circuit is energized.

Figures 3.2.2-3 through 3.2.2-11 present the result of this portion of the parametric study. The extremely large weight difference between figure 3.2.2-3 and 3.2.2-9 is the result of the different generator voltage and current levels. The extremely high levels of current require large contacts to keep the steady-state contact losses down to a reasonable value. In addition, the internal bus-work must be proportionately larger for these currents.

3.2.2.2 Tap-Changer

The mechanical configuration chosen for the tap-changer was that of a rotatable inner drum and a fixed outer drum both of cylindrical shape. All input

LINE CIRCUIT BREAKER SCHEMATIC

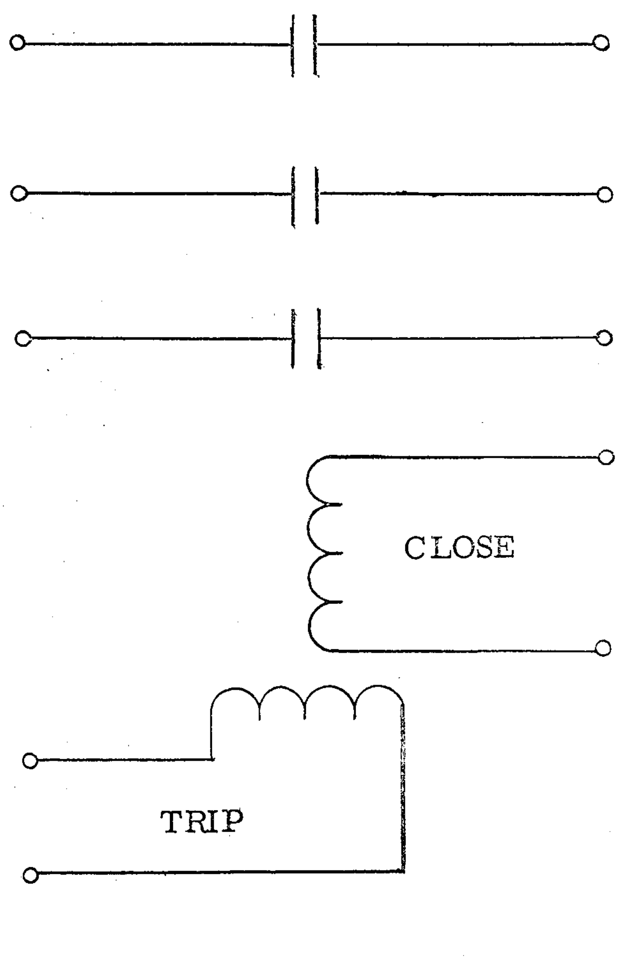


Figure 3. 2. 2-2

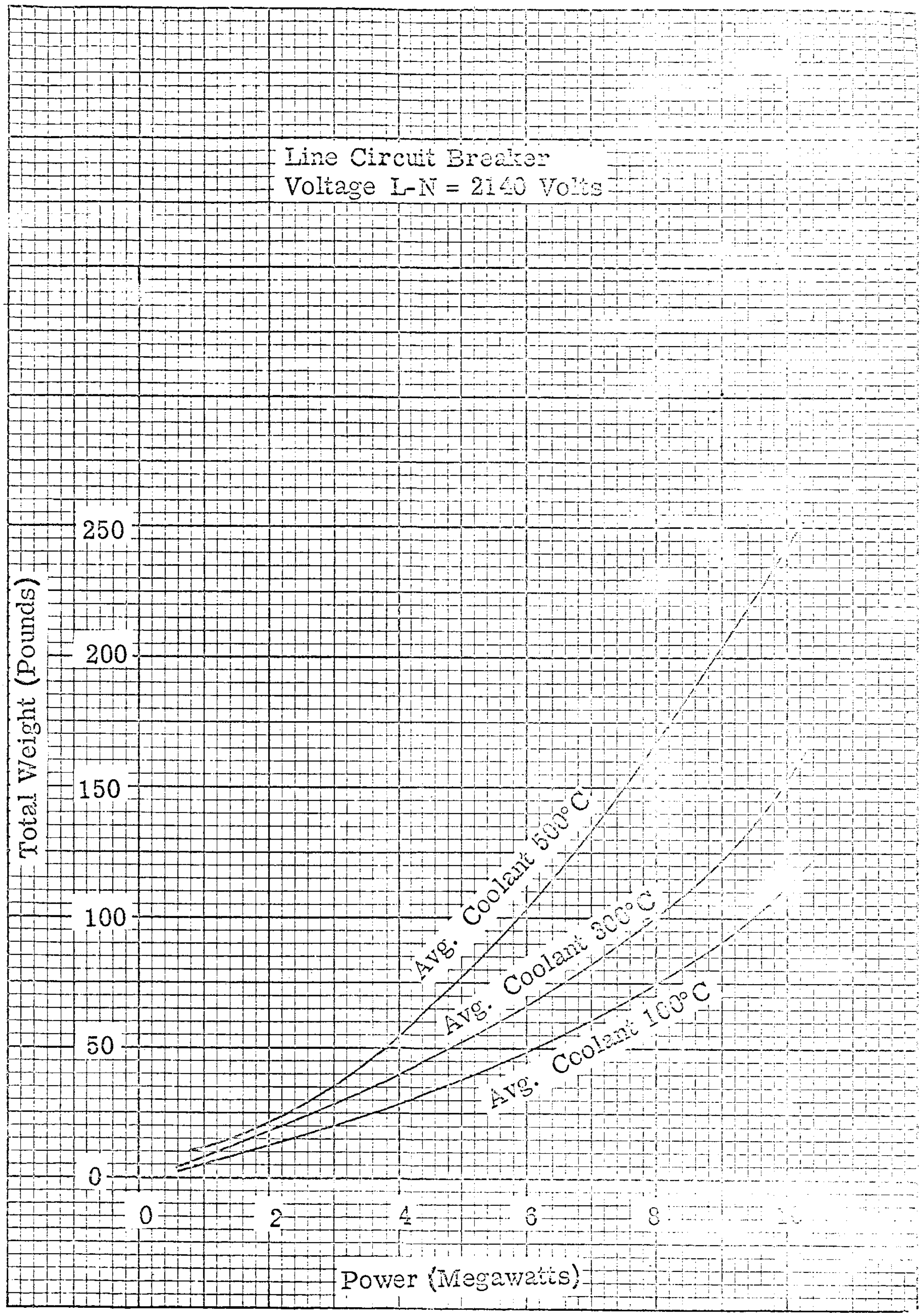

Line Circuit Breaker
Voltage L-N = 2140 Volts
Total Weight (Pounds)
250
200
150
100
50
0
0
2
4
6
8
Power (Megawatts)
Avg. Coolant 500°C
Avg. Coolant 300°C
Avg. Coolant 100°C

Figure 3. 2. 2-3

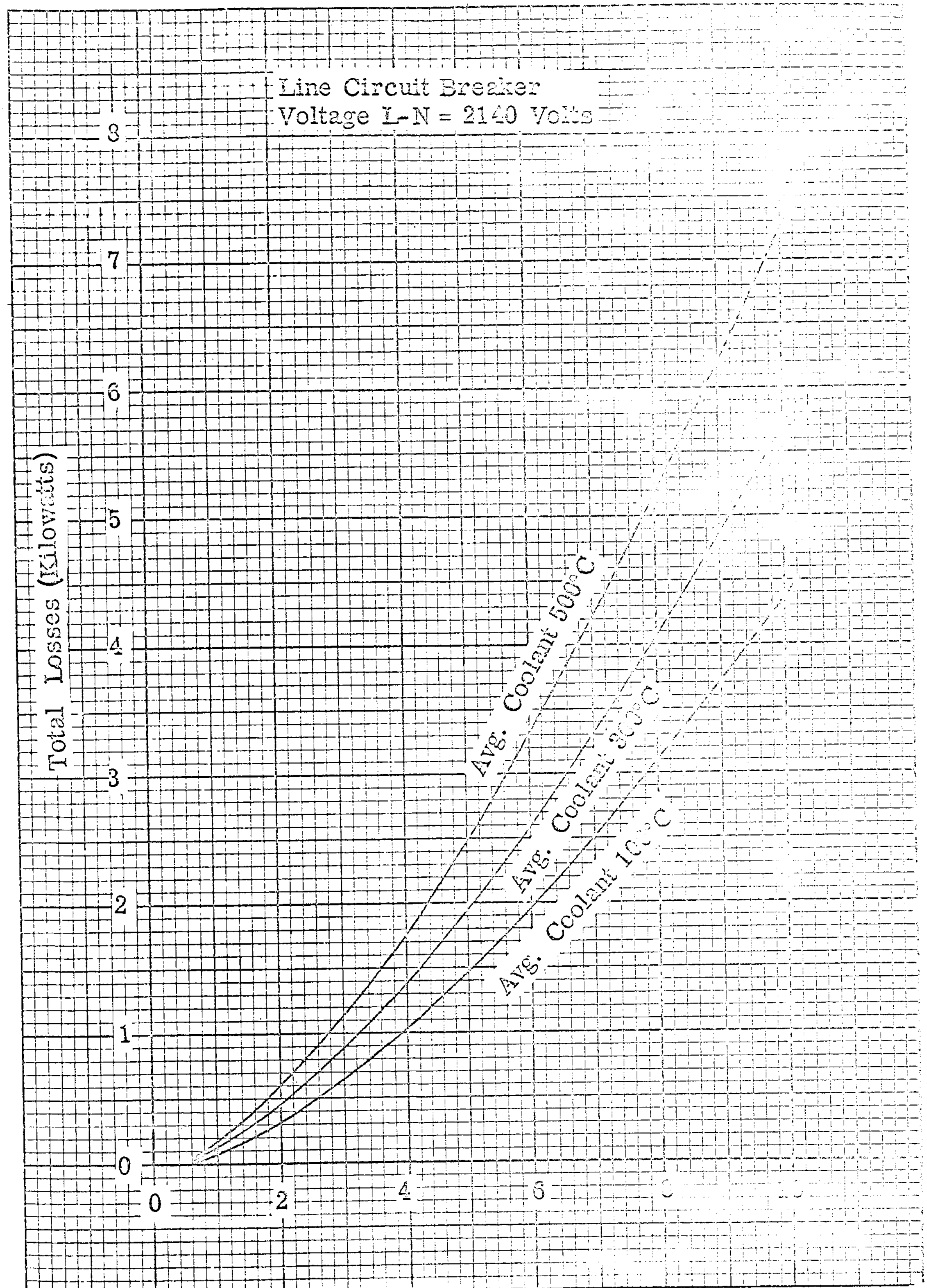

Line Circuit Breaker
Voltage L-N = 2140 Volts
Total Losses (Kilowatts)
Avg. Coolant 500°C
Avg. Coolant 300°C
0
1
2
3
4
5
6
7
8
0
2
4
6

Figure 3. 2. 2-4

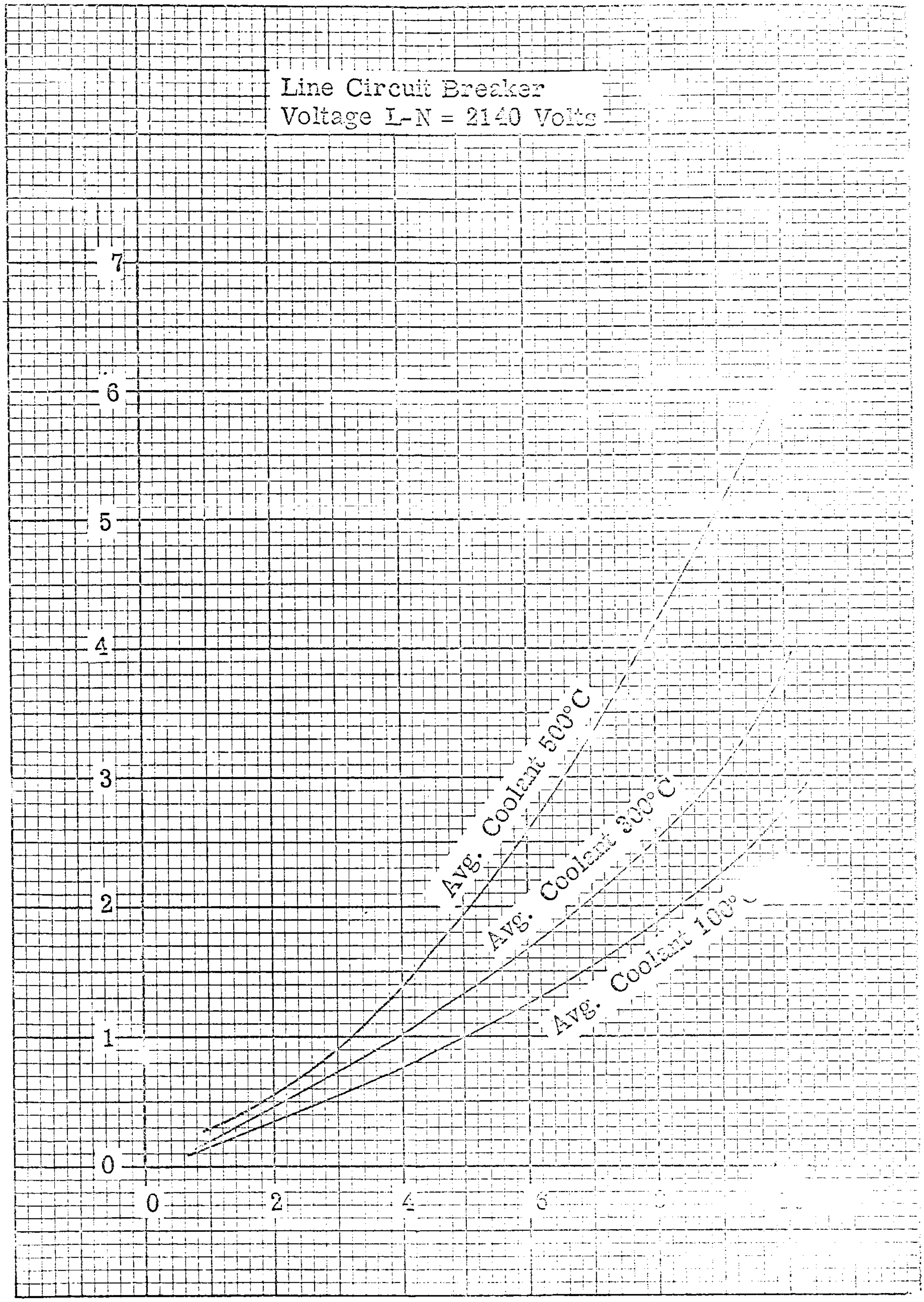

Line Circuit Breaker
Voltage L-N = 2140 Volts
Avg. Coolant 500°C
Avg. Coolant 300°C
Avg. Coolant 100°C
7
6
5
4
3
2
1
0
0
2
4
6

Figure 3. 2. 2-5

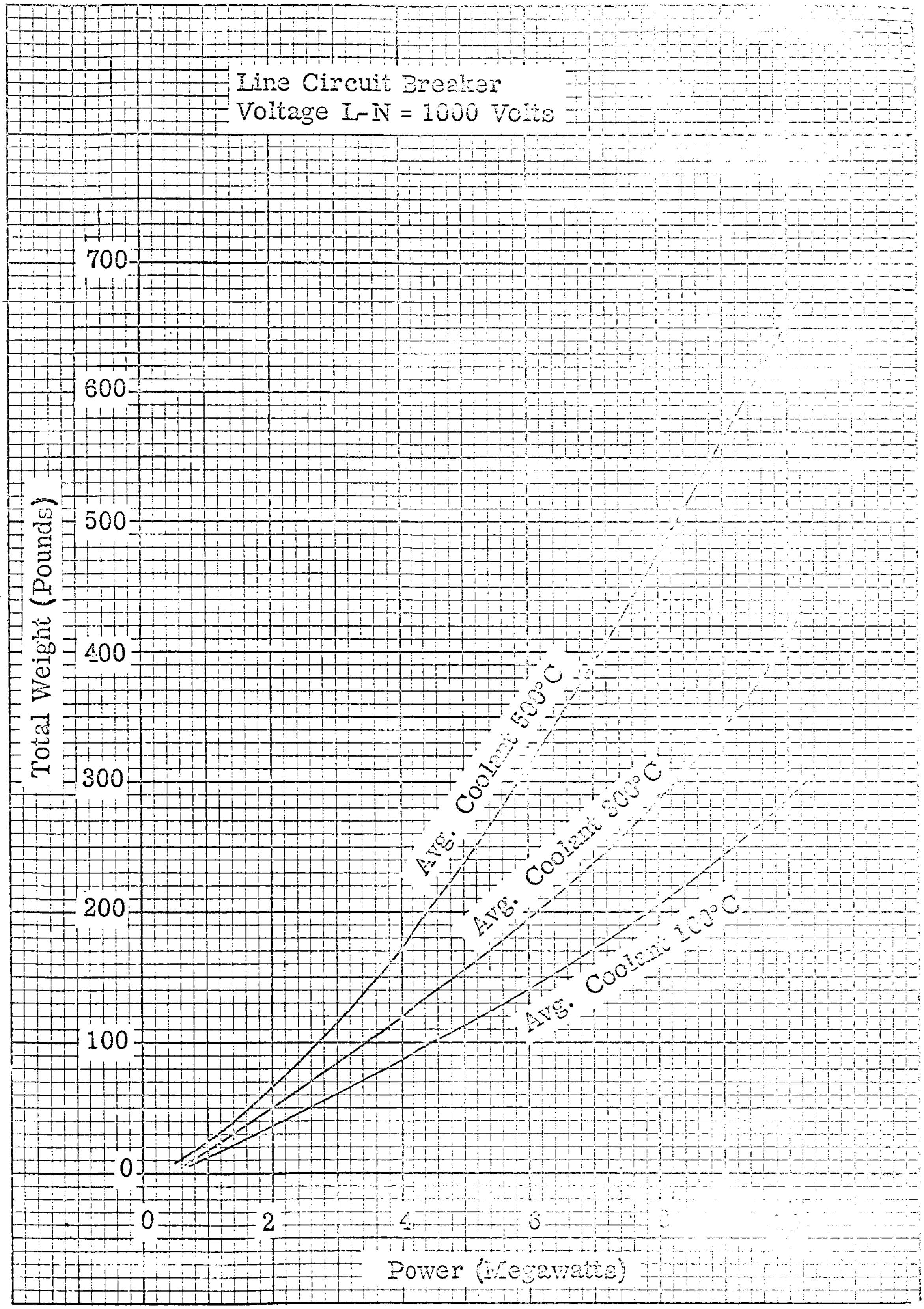

Line Circuit Breaker
Voltage L-N = 1000 Volts
700
600
500
400
300
200
100
0
Total Weight (Pounds)
Avg. Coolant 500°C
Avg. Coolant 300°C
Avg. Coolant 100°C
0
2
4
6
Power (Megawatts)

Figure 3. 2. 2-6

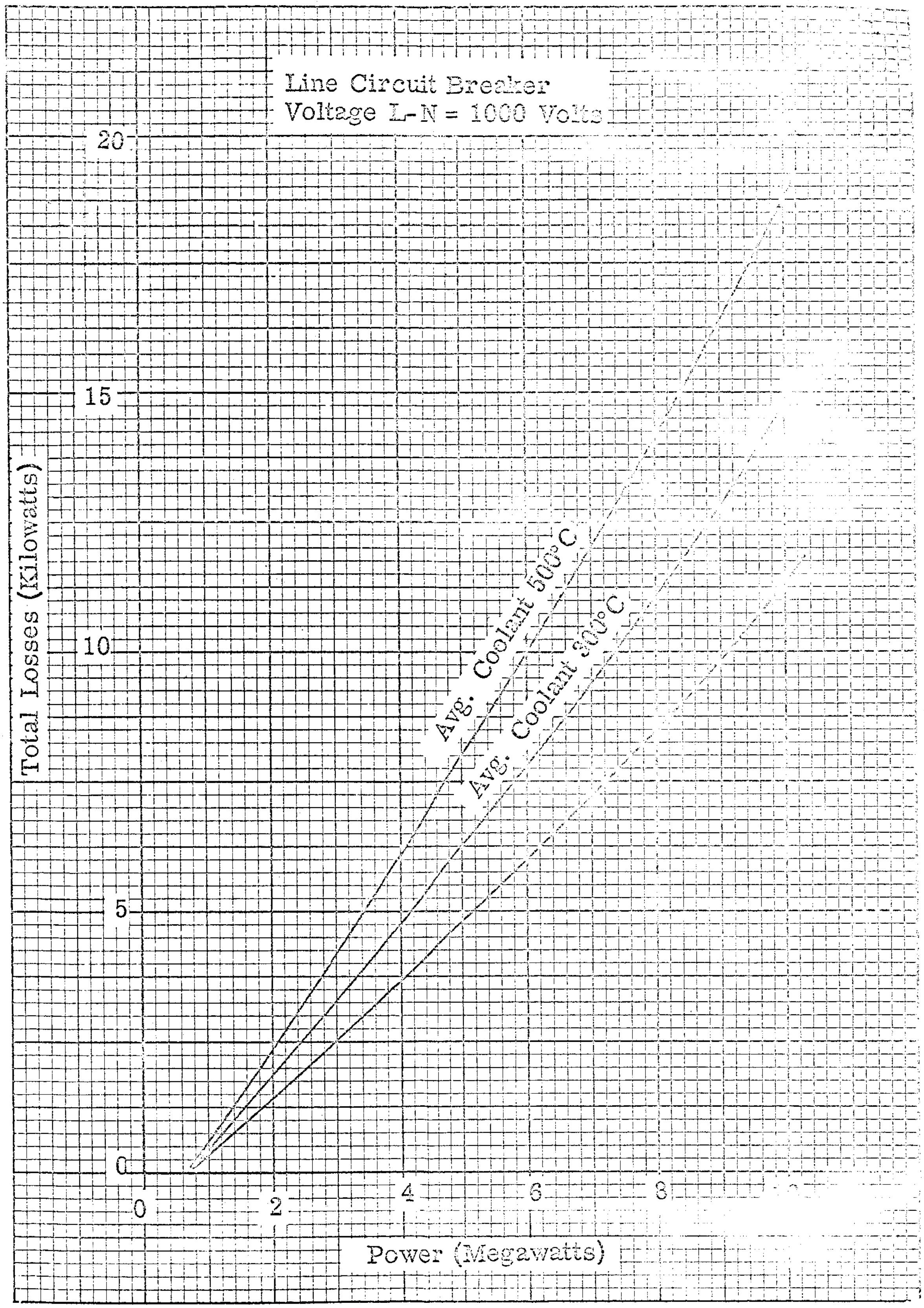
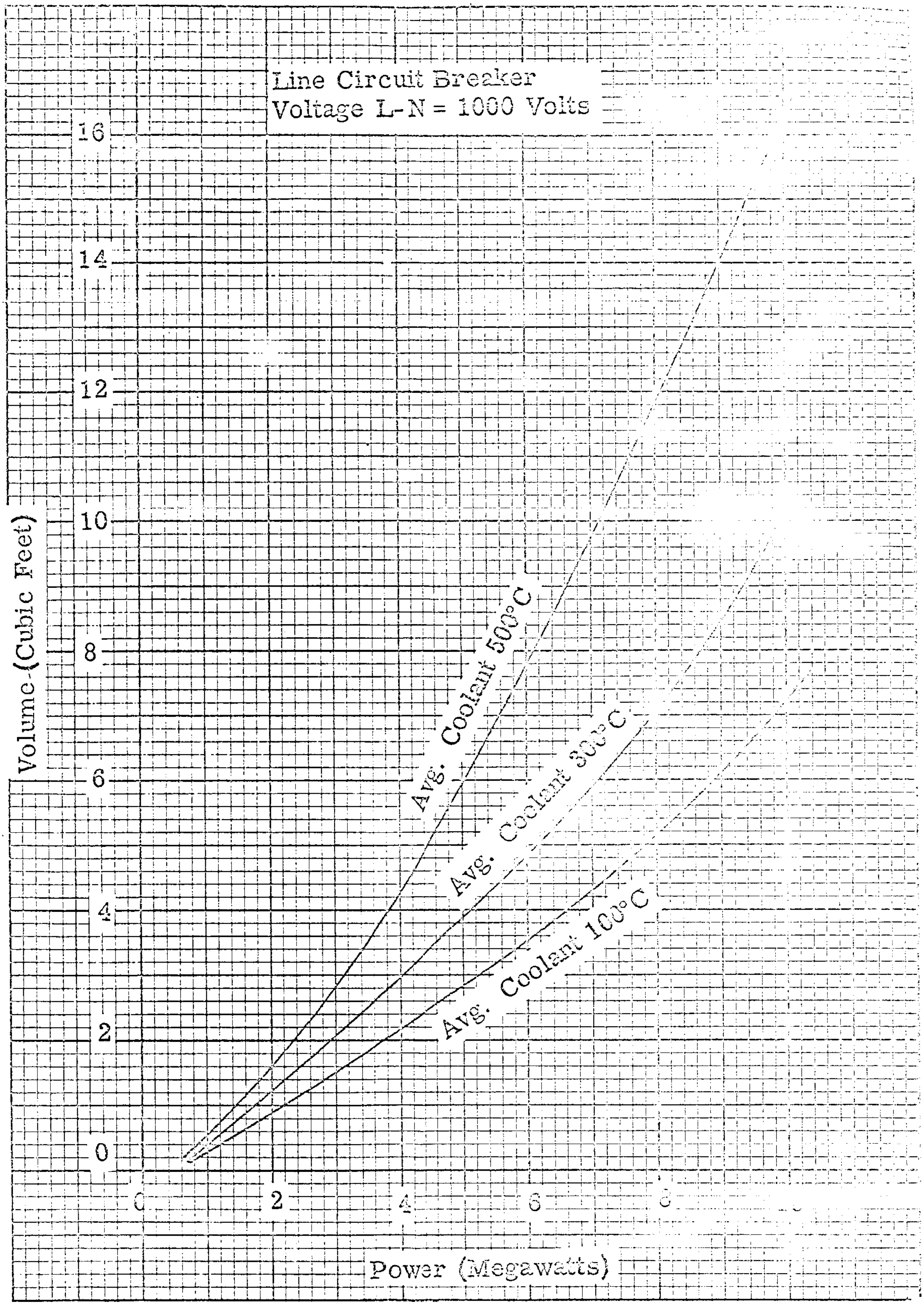
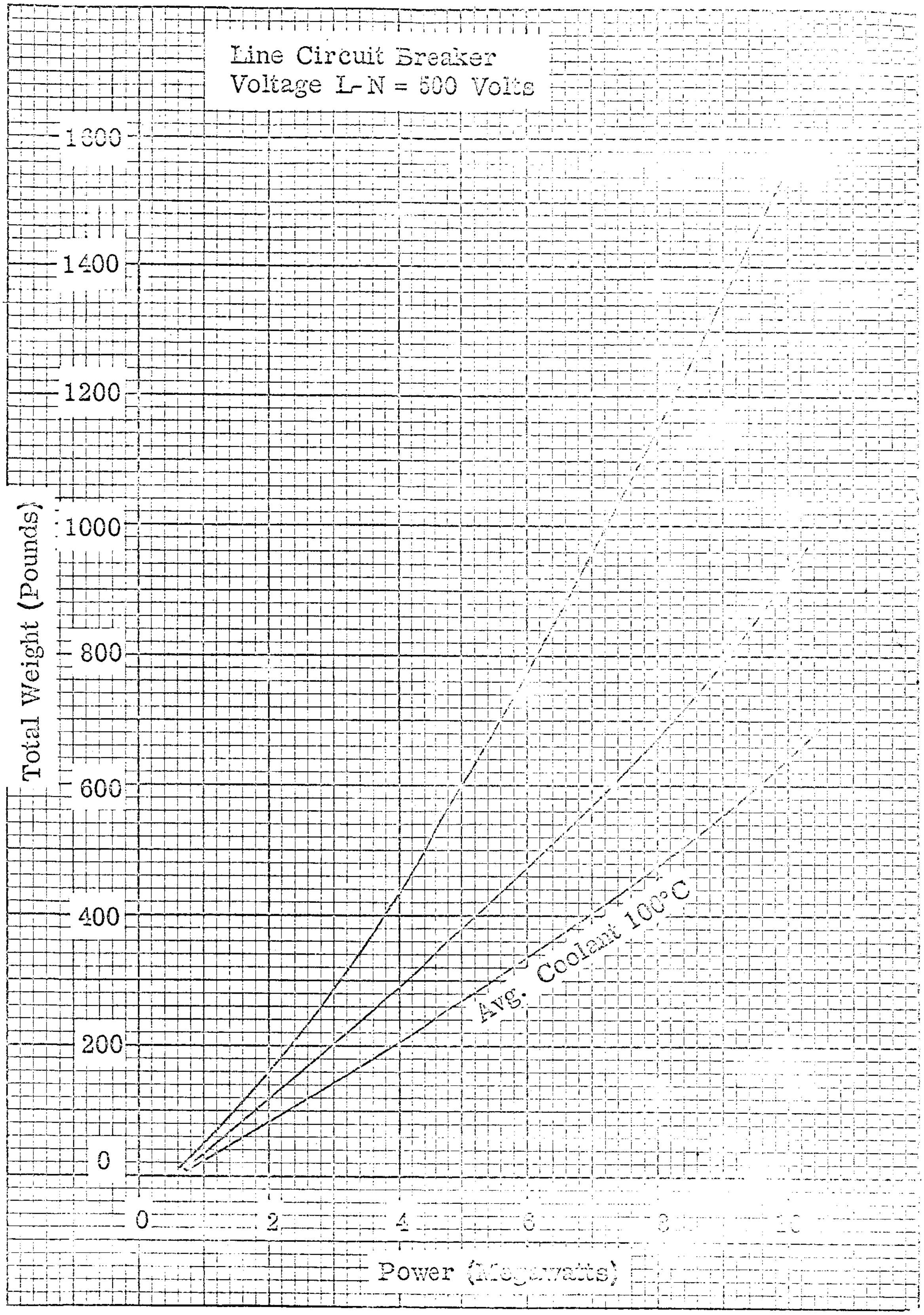

Line Circuit Breaker
Voltage L-N = 1000 Volts
Total Losses (Kilowatts)
20
15
10
5
0
0
2
4
6
8
Power (Megawatts)
Avg. Coolant 500°C
Avg. Coolant 300°C

Figure 3. 2. 2-7



Line Circuit Breaker
Voltage L-N = 1000 Volts
Volume-(Cubic Feet)
16
14
12
10
8
6
4
2
0
0
2
4
6
8
Avg. Coolant 500°C
Avg. Coolant 300°C
Avg. Coolant 100°C
Power (Megawatts)

Figure 3. 2. 2-8



Line Circuit Breaker
Voltage L-N = 500 Volts
Total Weight (Pounds)
1600
1400
1200
1000
800
600
400
200
0
Avg. Coolant 100°C
0
2
4
6
8
10
Power (Megawatts)

Figure 3. 2. 2-9

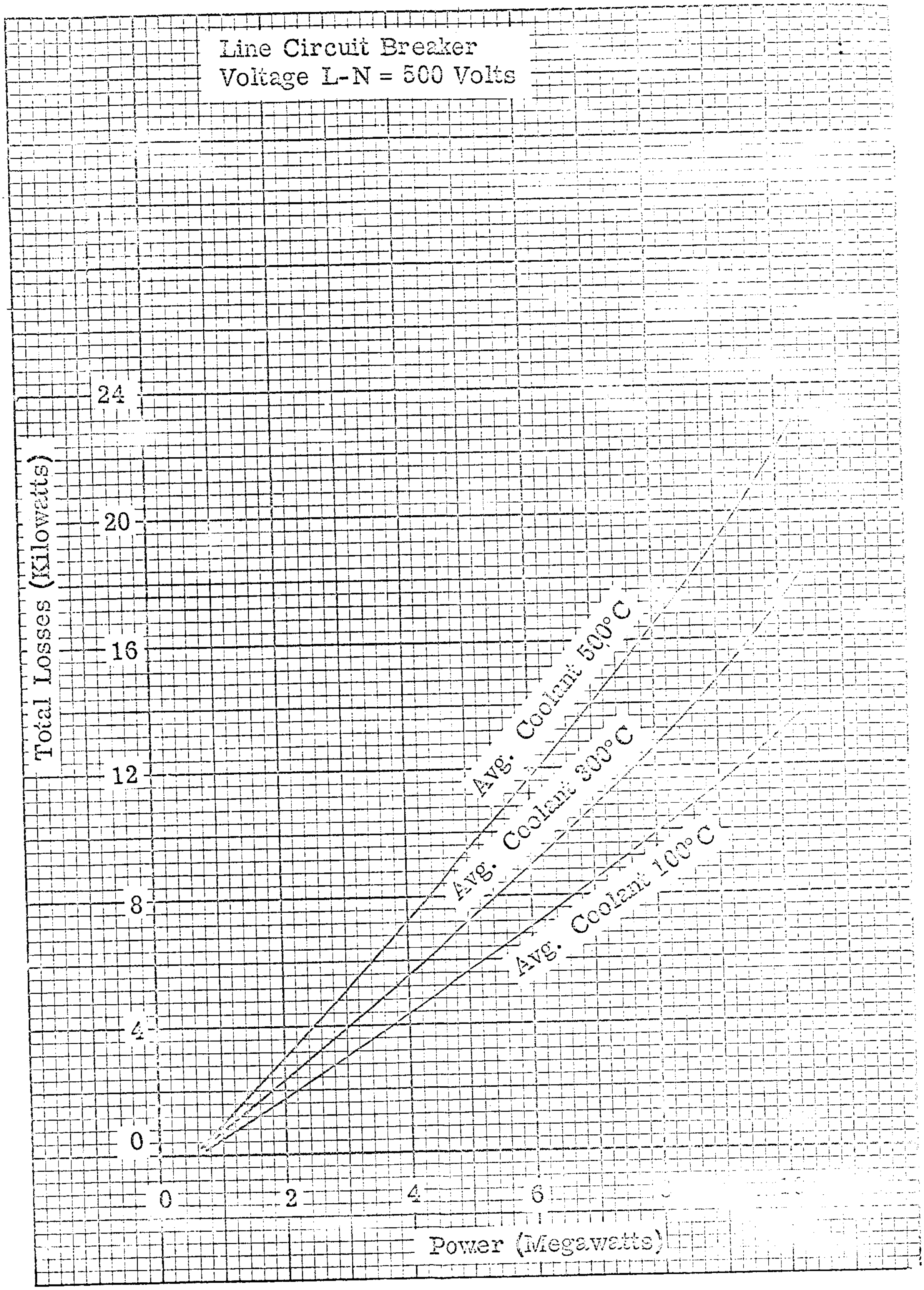


Figure 3. 2. 2-10

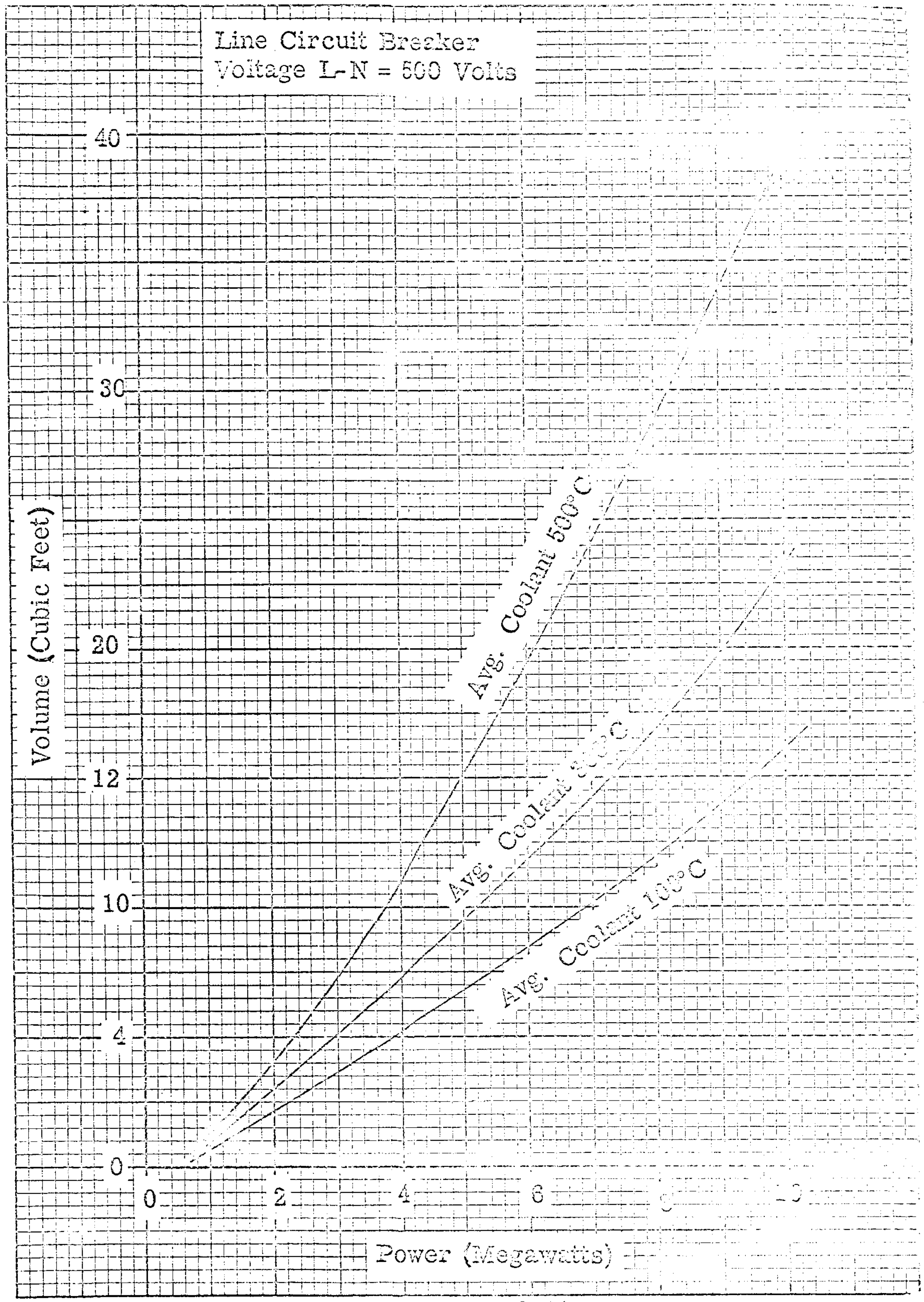


Figure 3. 2. 2-11

and output connections to the tap-changer are made on the outer drum. The inner drum is rotated by a driving mechanism from one angular station to the next such that contacts on the inner and outer drums are engaged.

Figure 3.2.2-12 shows the basic electrical function of the unit. On the outer drum, levels 1, 3, and 5 will be used as output connections to the transformer. The input connections to the tap-changer will be on levels 2, 4, and 6. For example, the input on level 2 of the outer drum is taken to level 2 of the inner drum by a contact and internal bus-work connected to level 1 of the inner drum. The inner drum level 1 is connected to the outer drum level 1 by contact that is dependent upon the position of the inner drum.

The input power is placed on the inner drum by means of a contact. This method was chosen in lieu of flexible bus work connected directly to the inner drum because it is more feasible to develop the contacts than to develop heavy bus work which is flexible and also reliable in a vacuum. Flexible copper braid, for example, was avoided because of the probability that each individual strand would eventually cold weld in a vacuum thus defeating its original purpose.

Figures 3.2.2-13 through 3.2.2-27 graphically present the results of this portion of the study. Figures 3.2.2-13 through 3.2.2-21 are for the weight, volume and losses for a four-tap tap-changer. Figure 3.2.2-22 through 3.2.2-27 show the weights of two-tap output and six-tap output tap-changers at the 1000/1732 voltage level. The two and six-tap output units were included for better weight evaluations of variable voltage systems.

TAP CHANGER SCHEMATIC

(4 Tap Output)

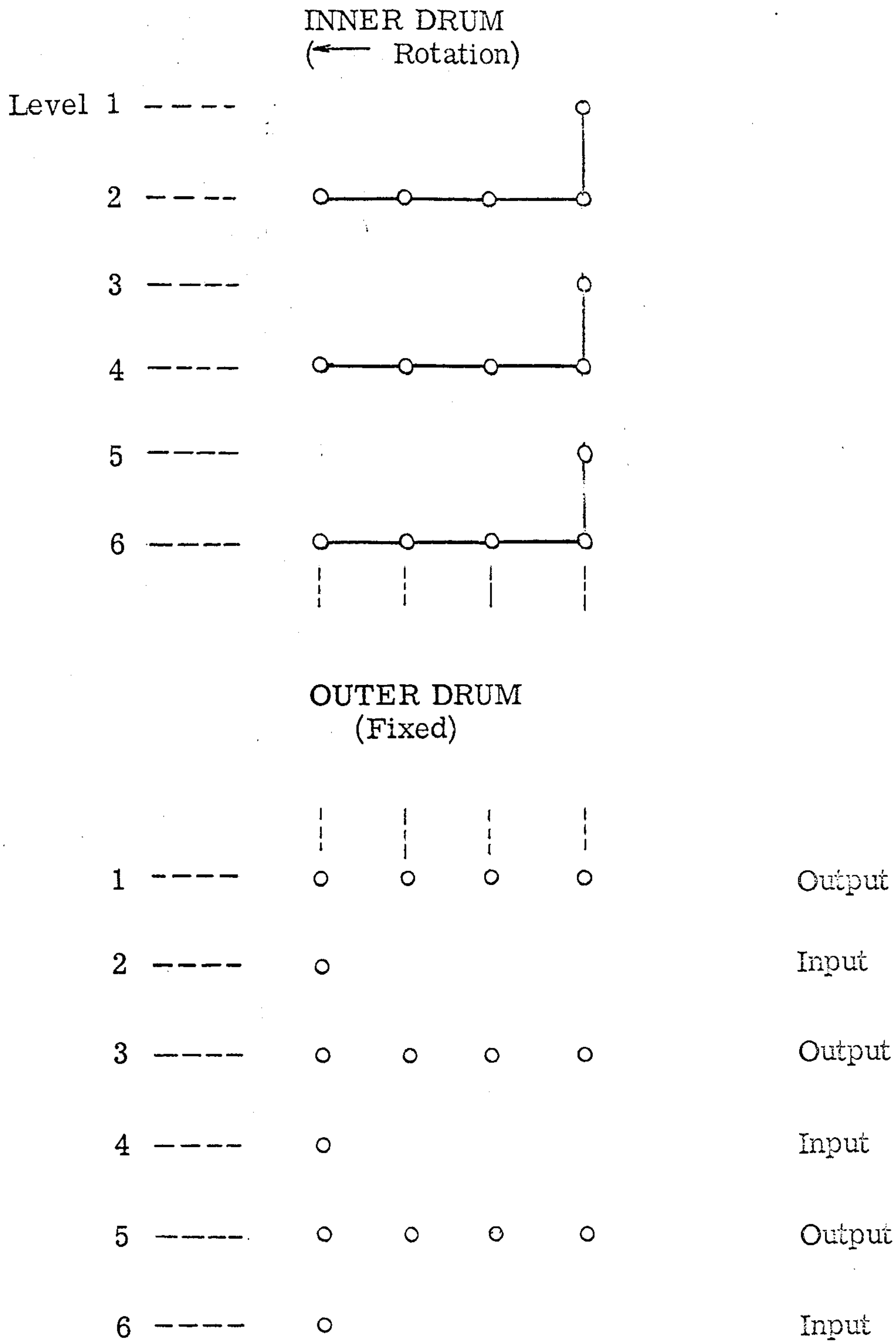


Figure 3. 2. 2-12

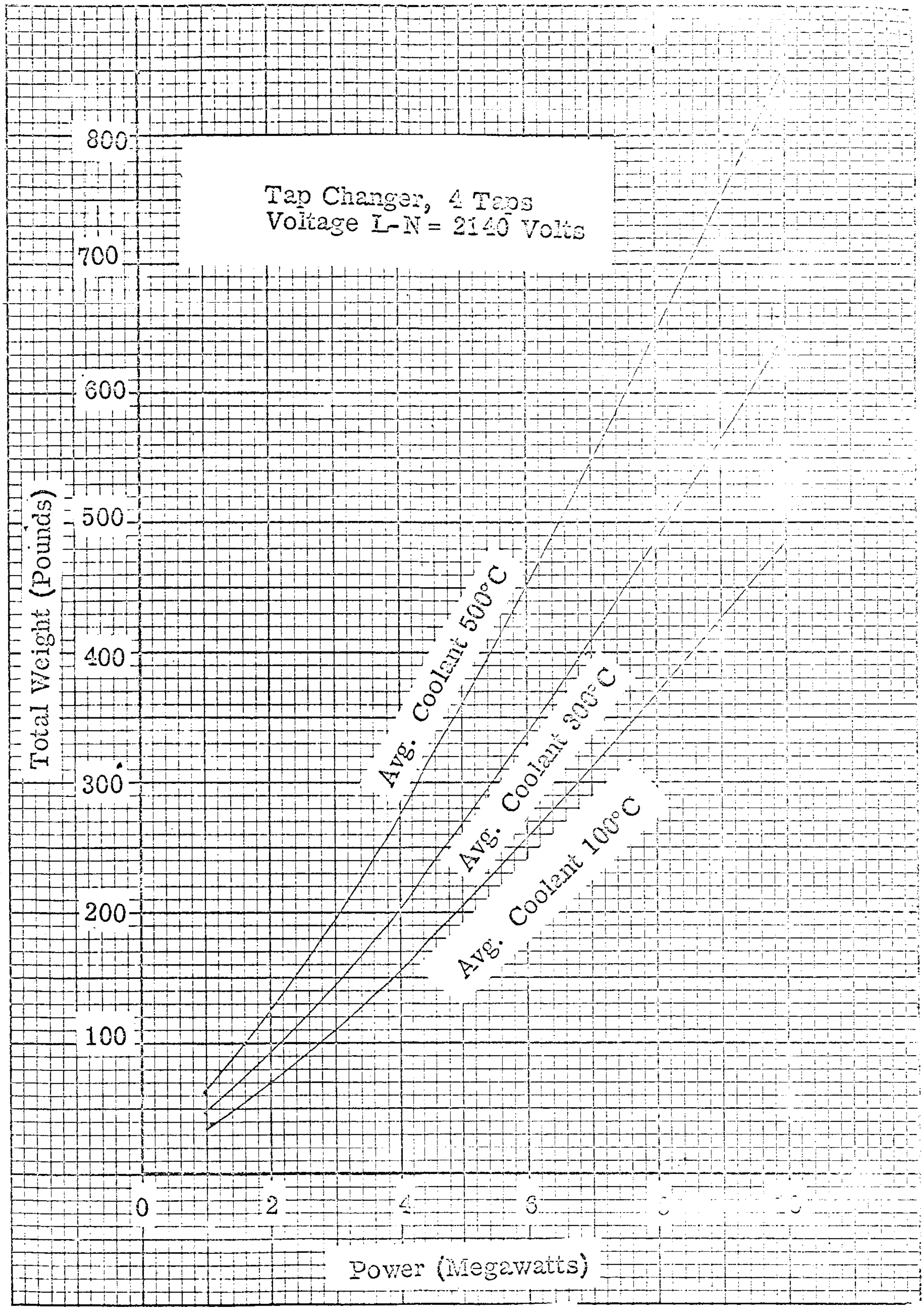


Figure 3. 2. 2-13

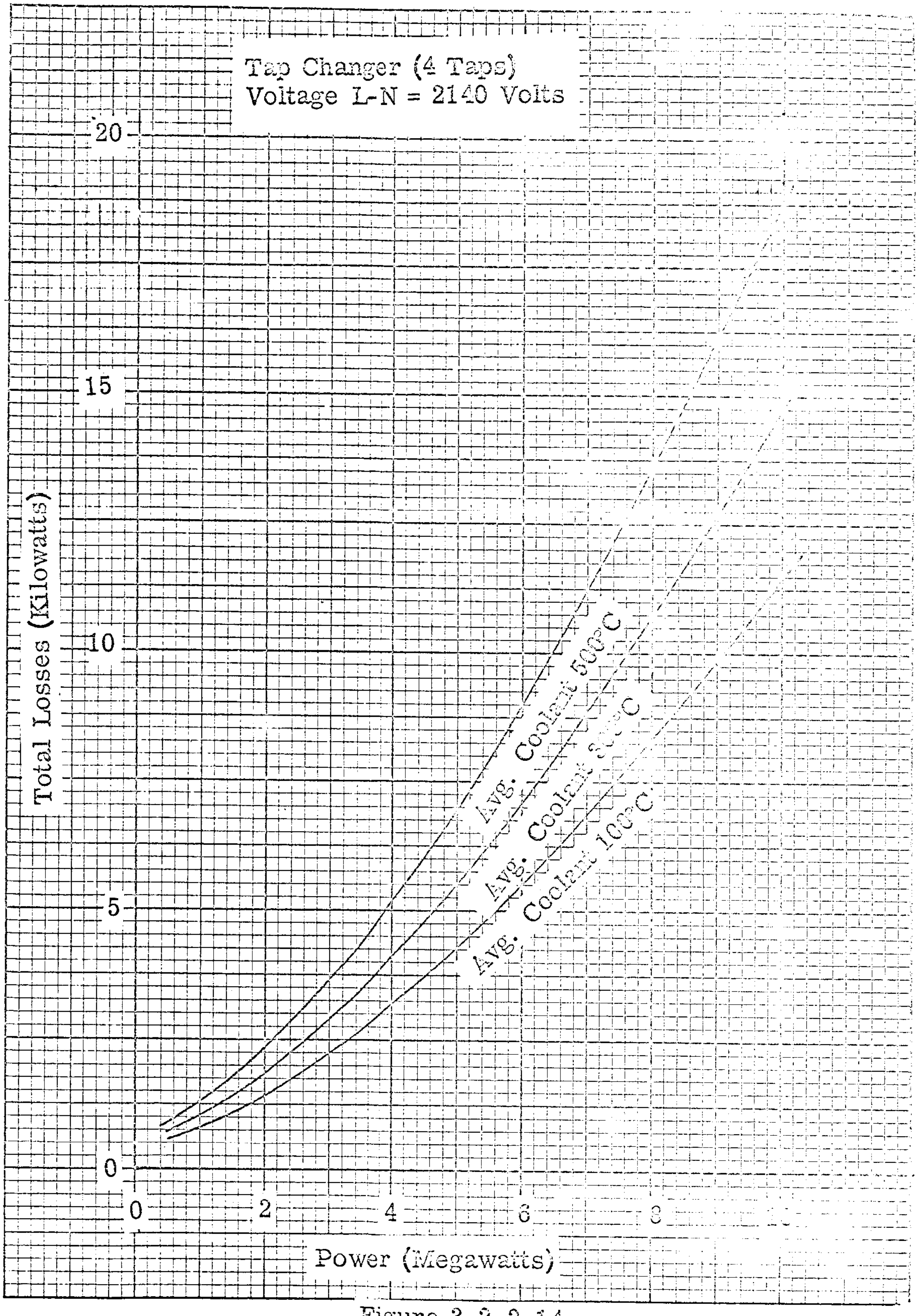


Figure 3. 2. 2-14

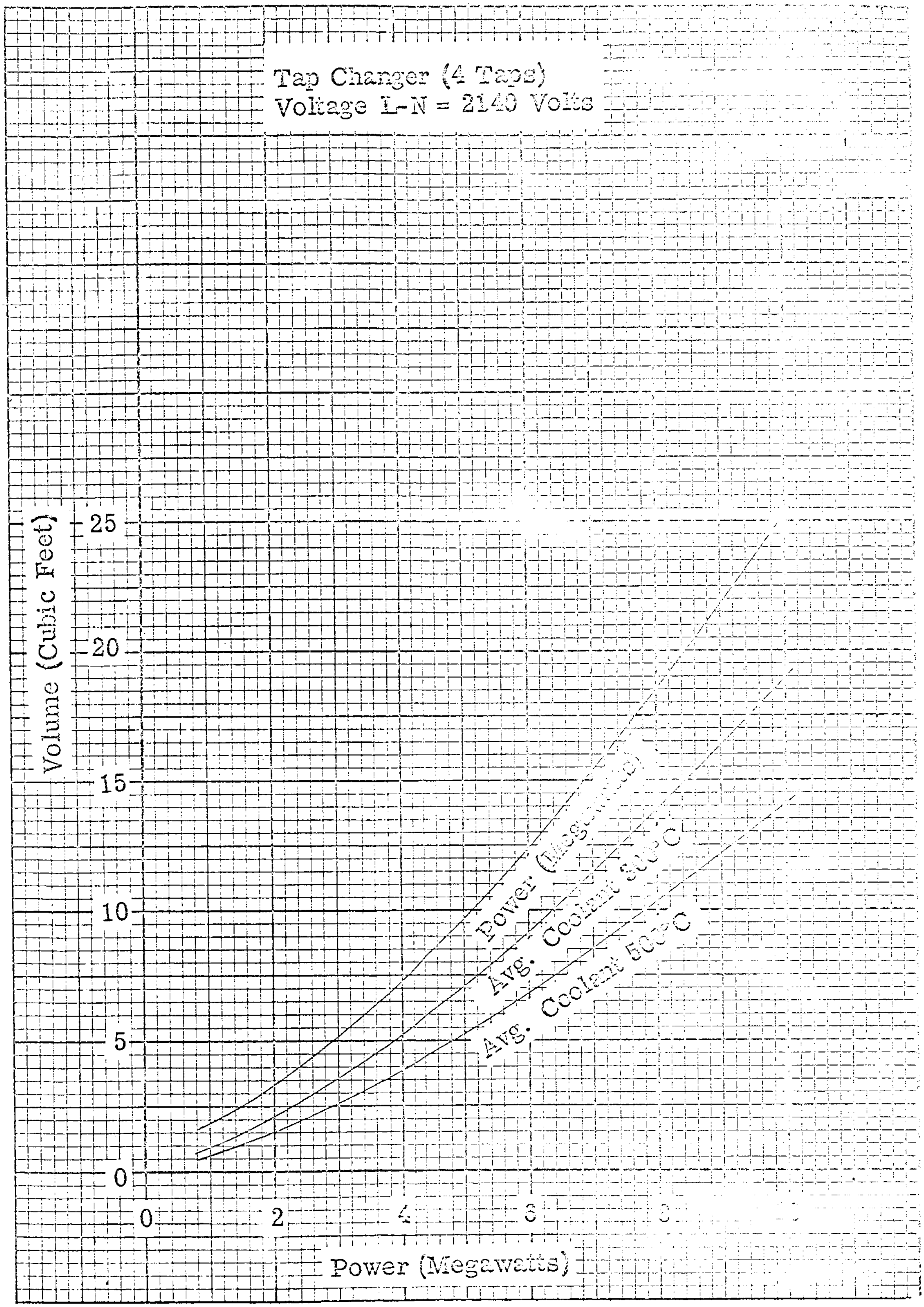


Figure 3. 2. 2-15

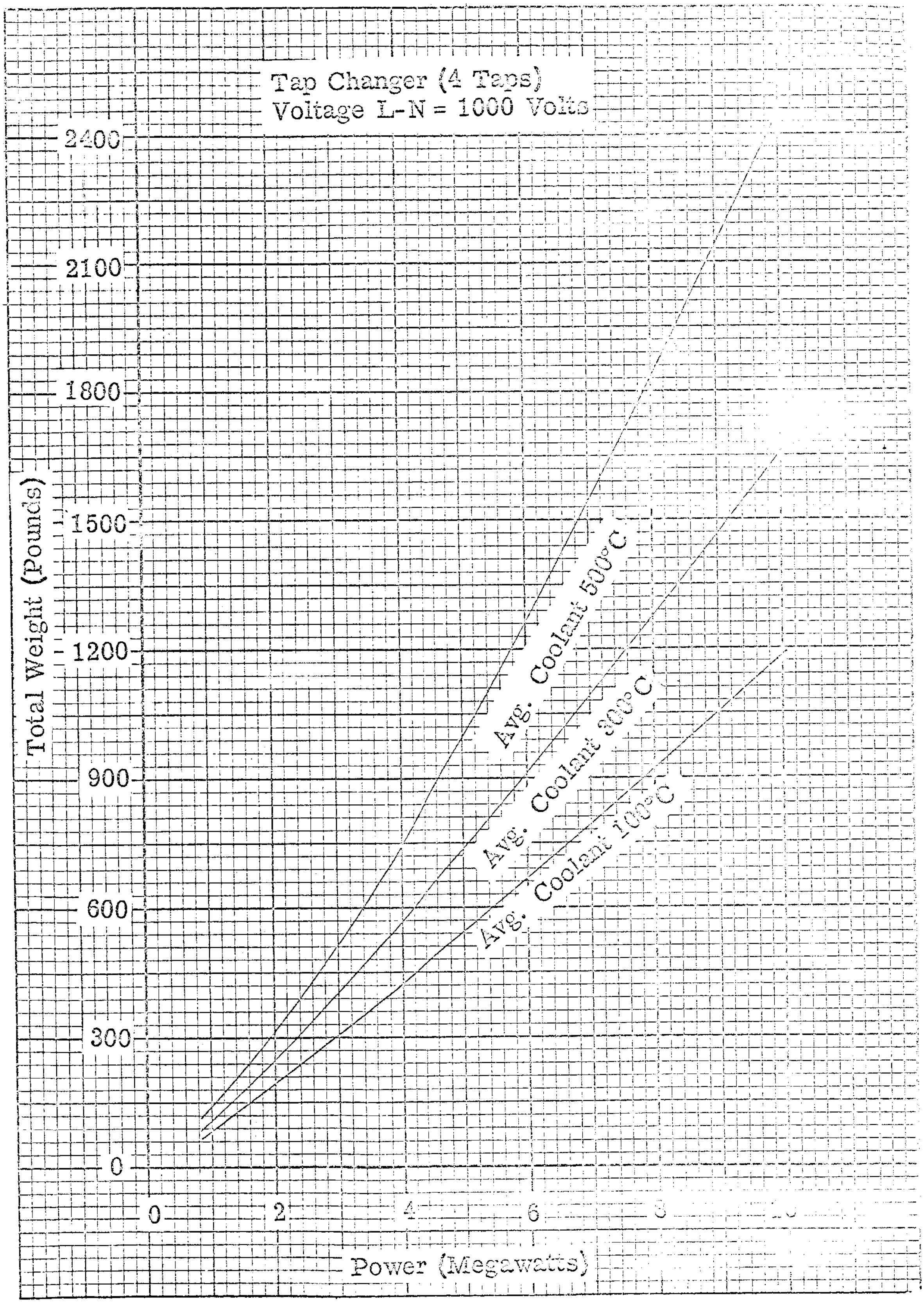


Figure 3. 2. 2-16

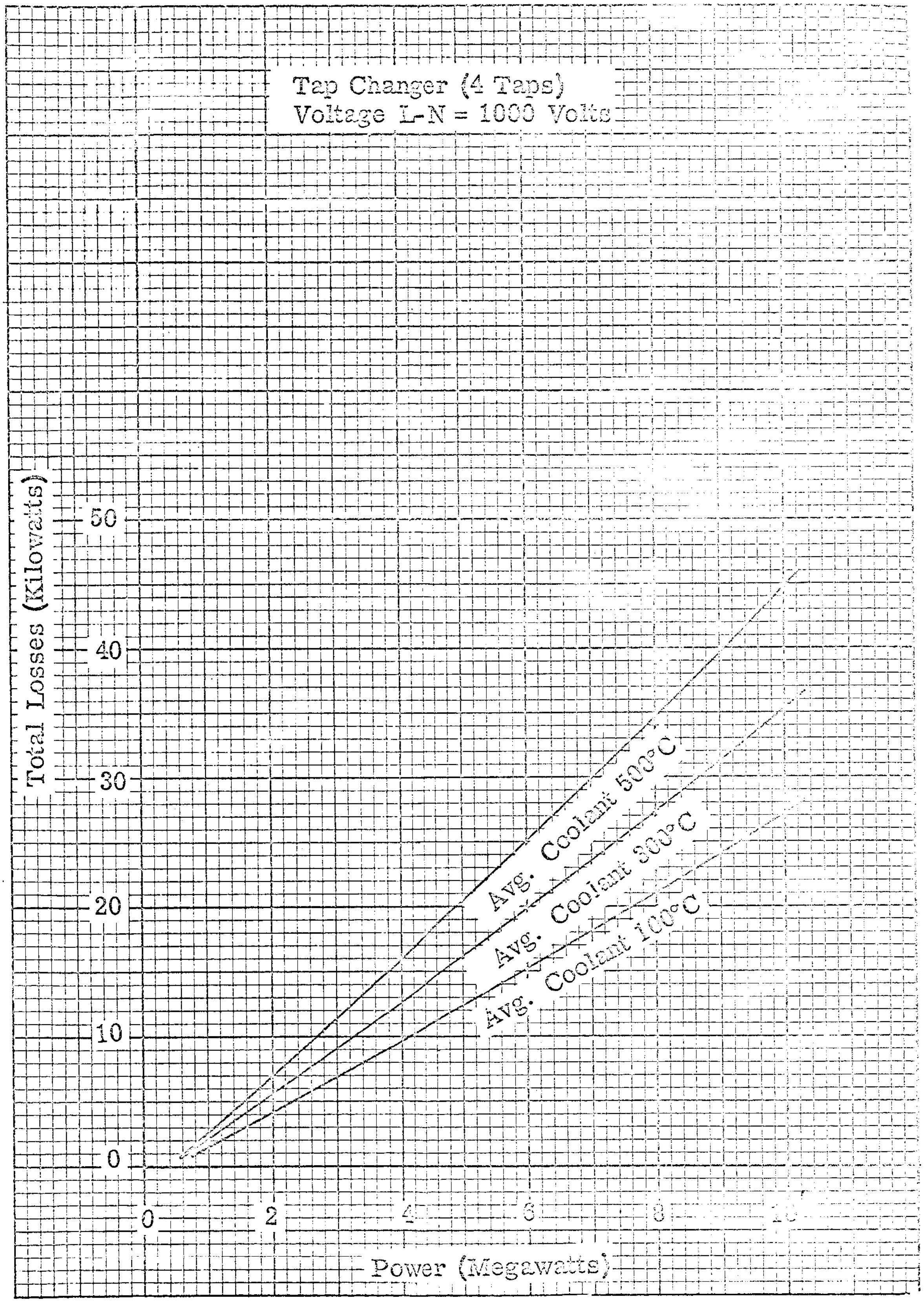


Figure 3. 2. 2-17

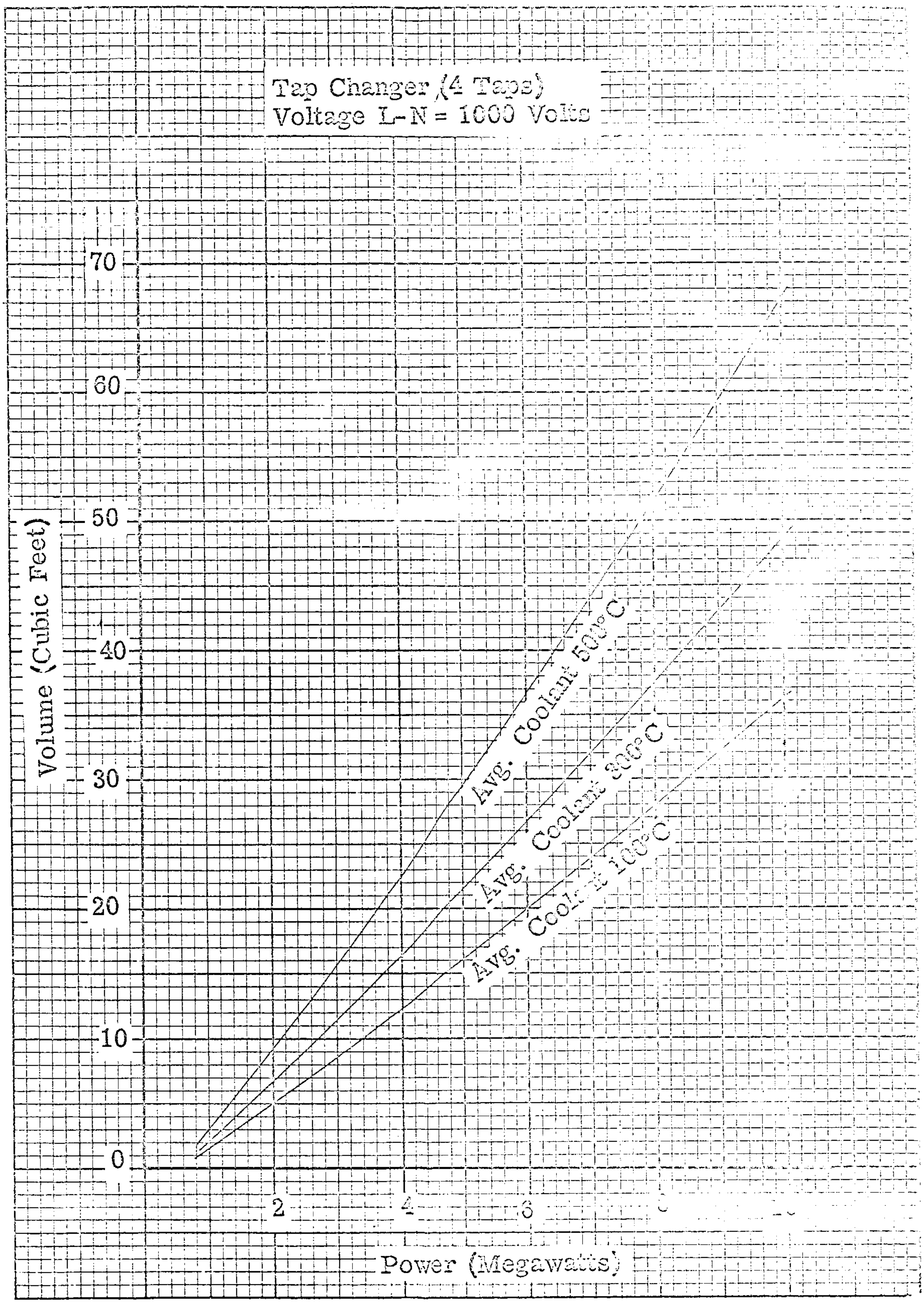


Figure 3. 2. 2-18

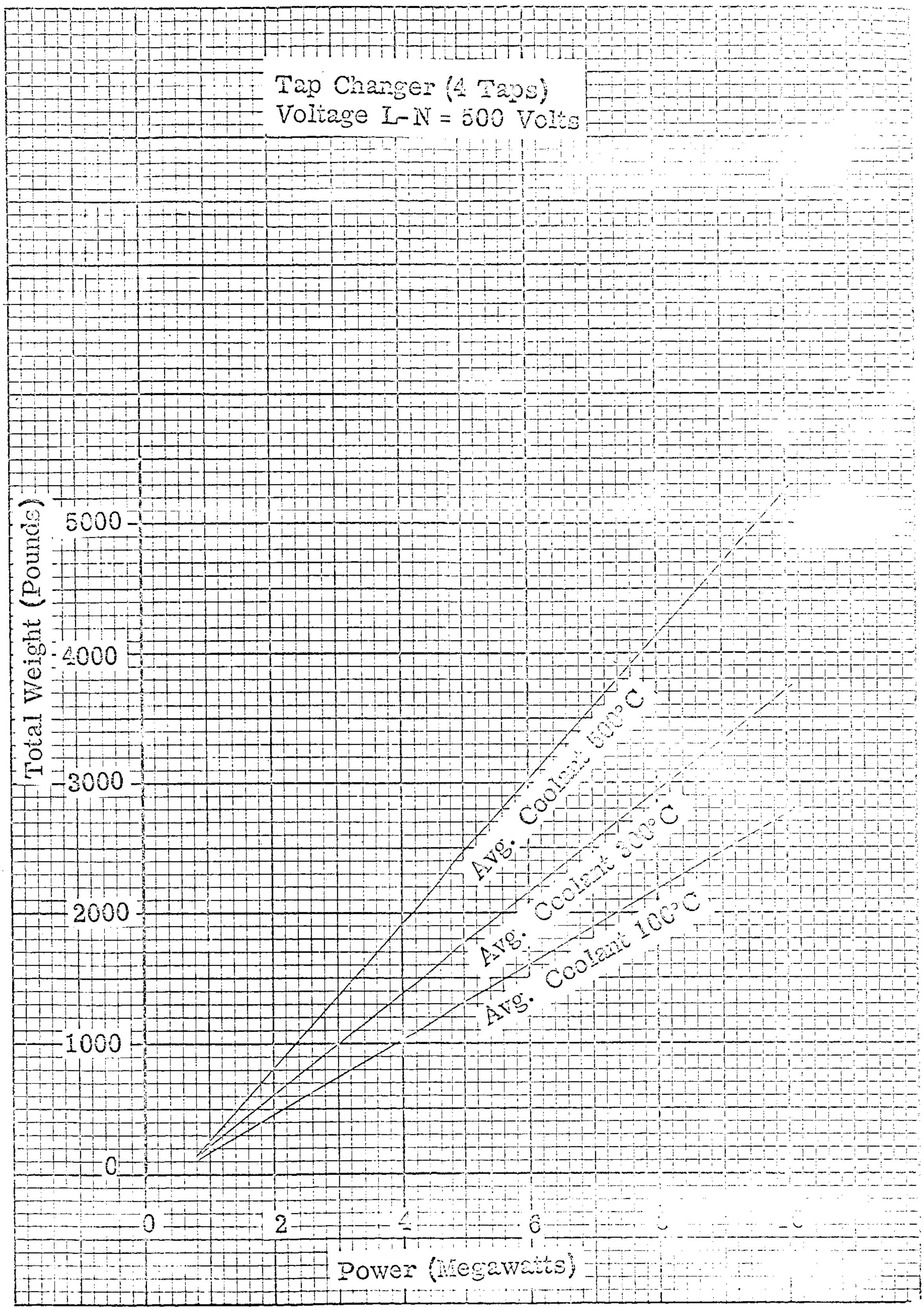


Figure 3. 2. 2-19

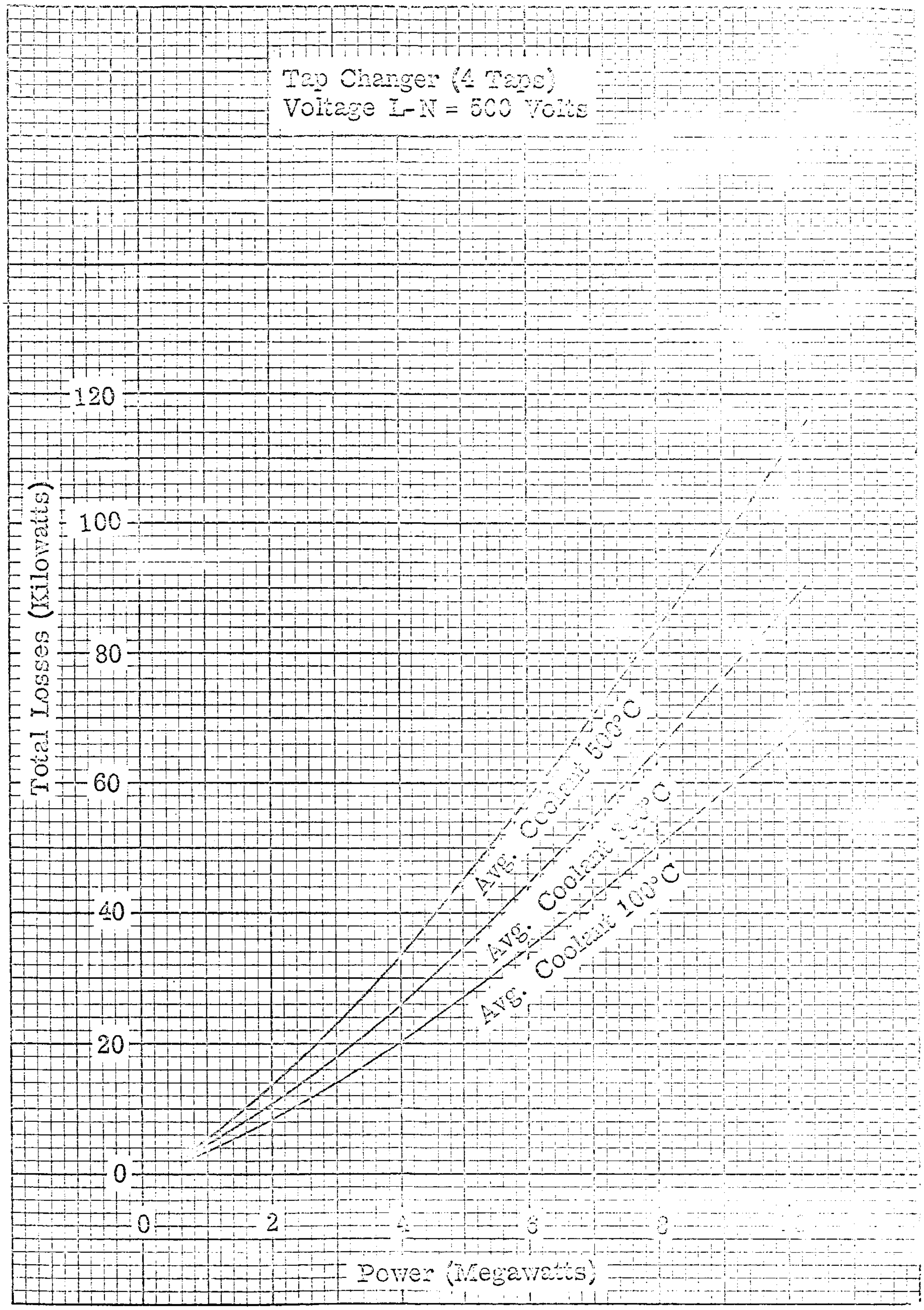


Figure 3.2.2-20

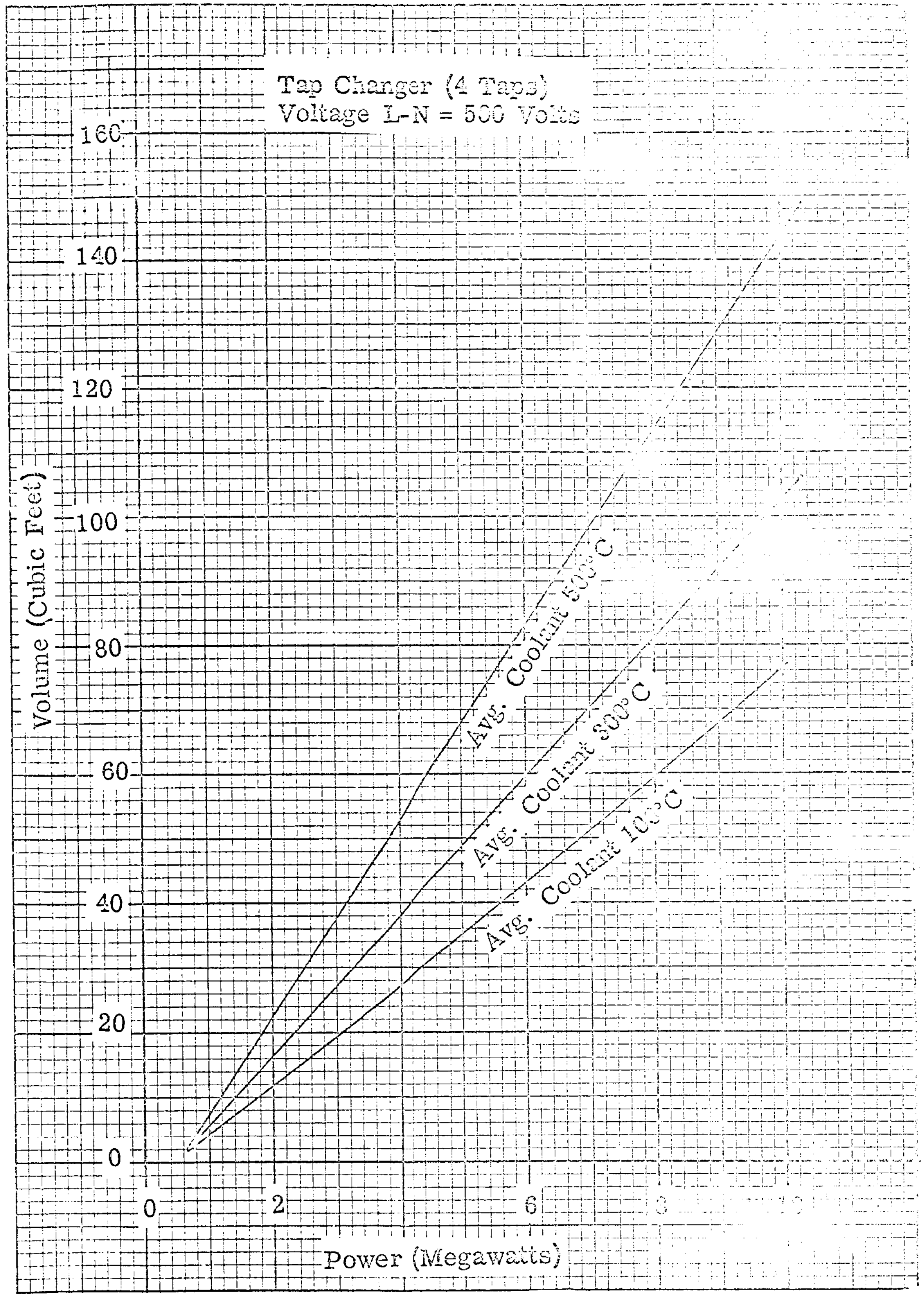


Figure 3. 2. 2-21

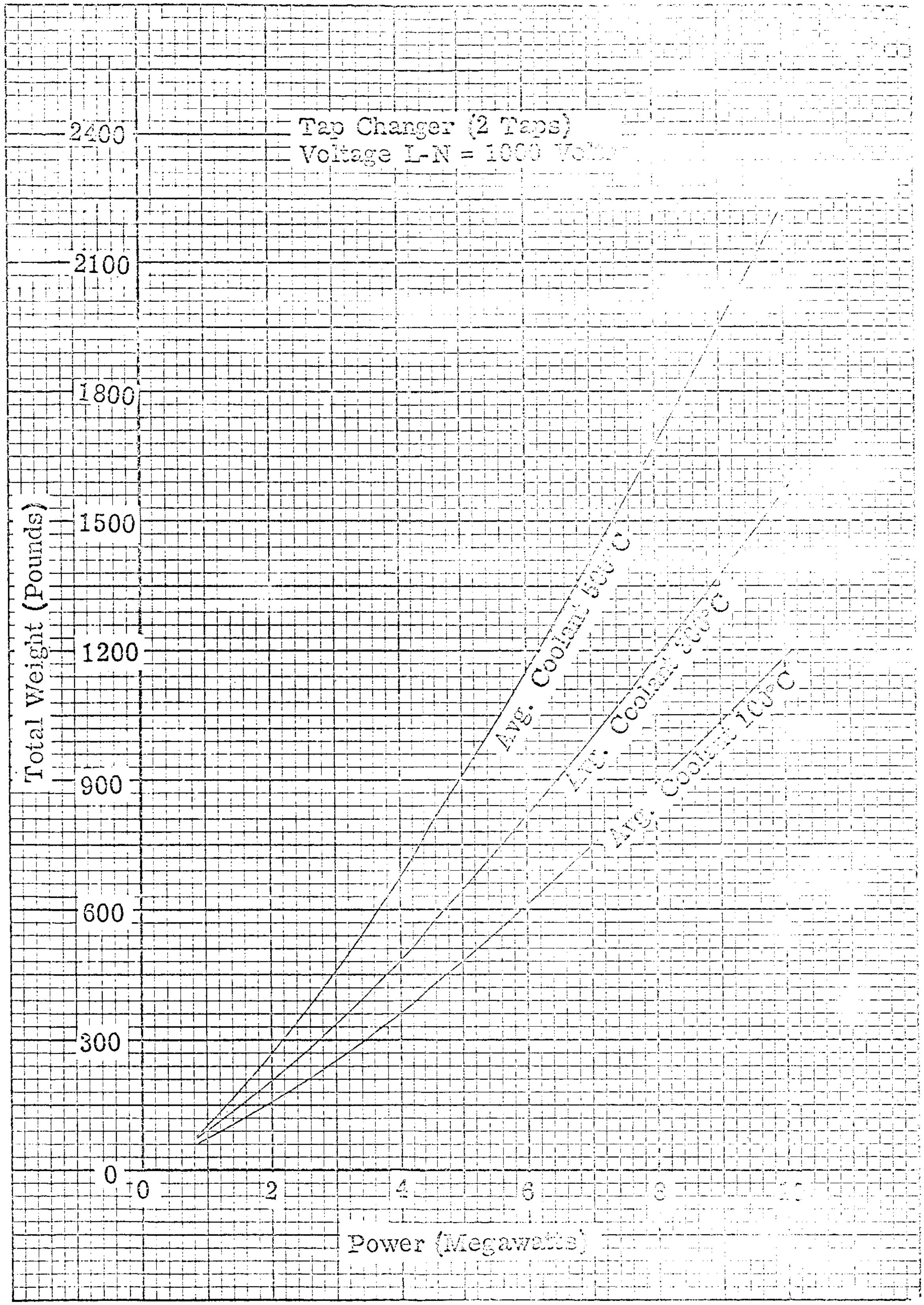


Figure 3.2.2-22

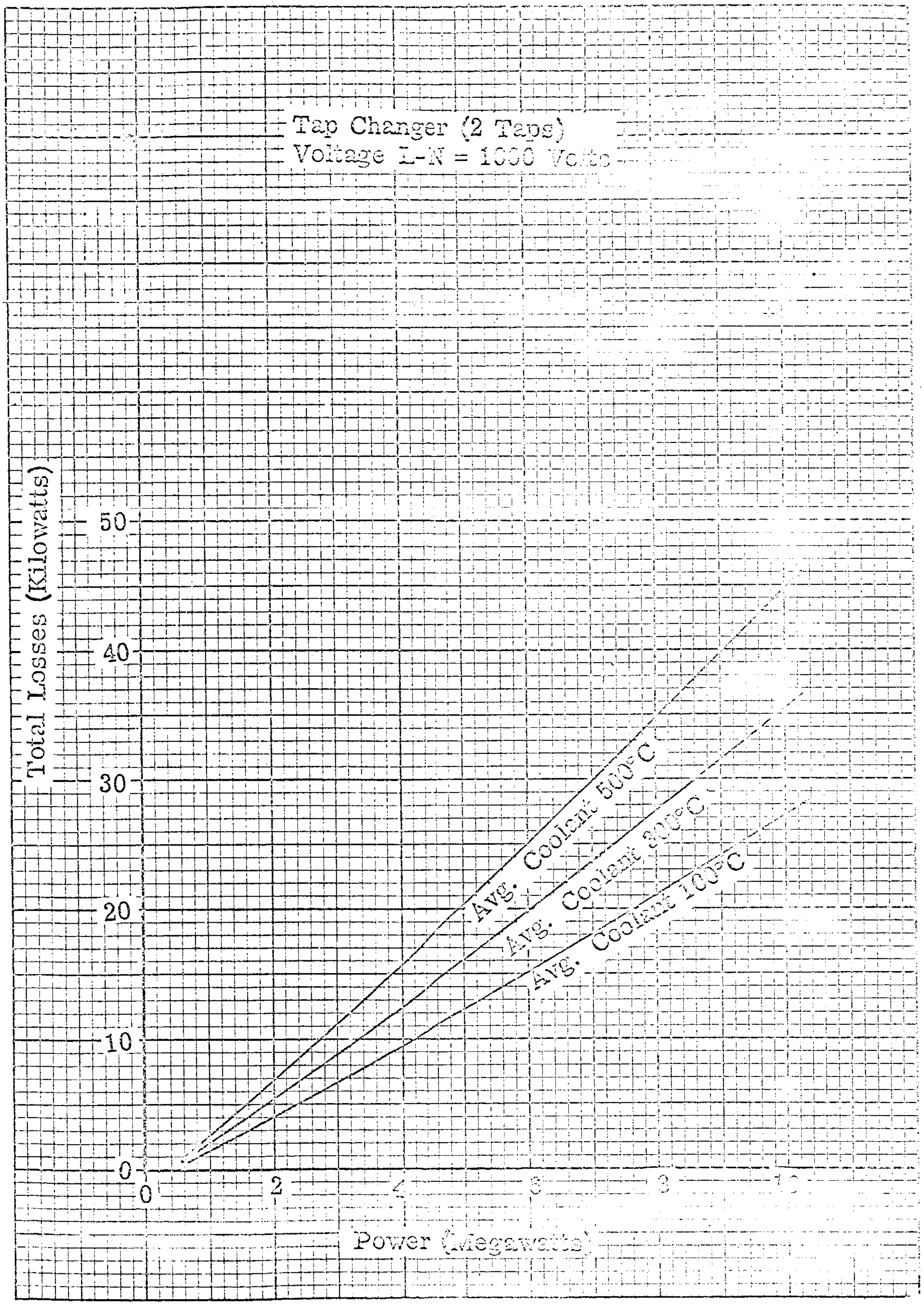


Figure 3.2.2-23

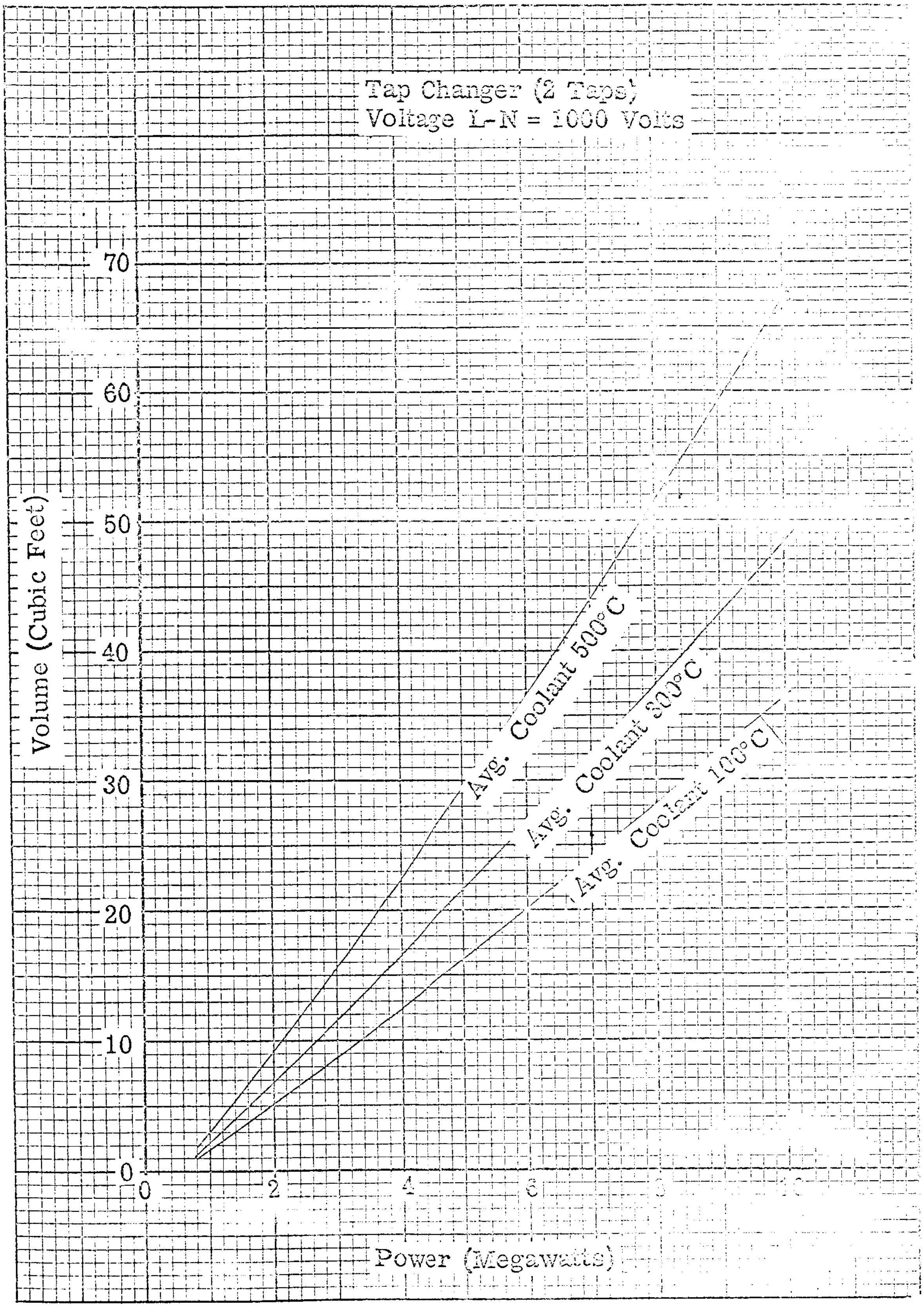


Figure 3.2.2-24

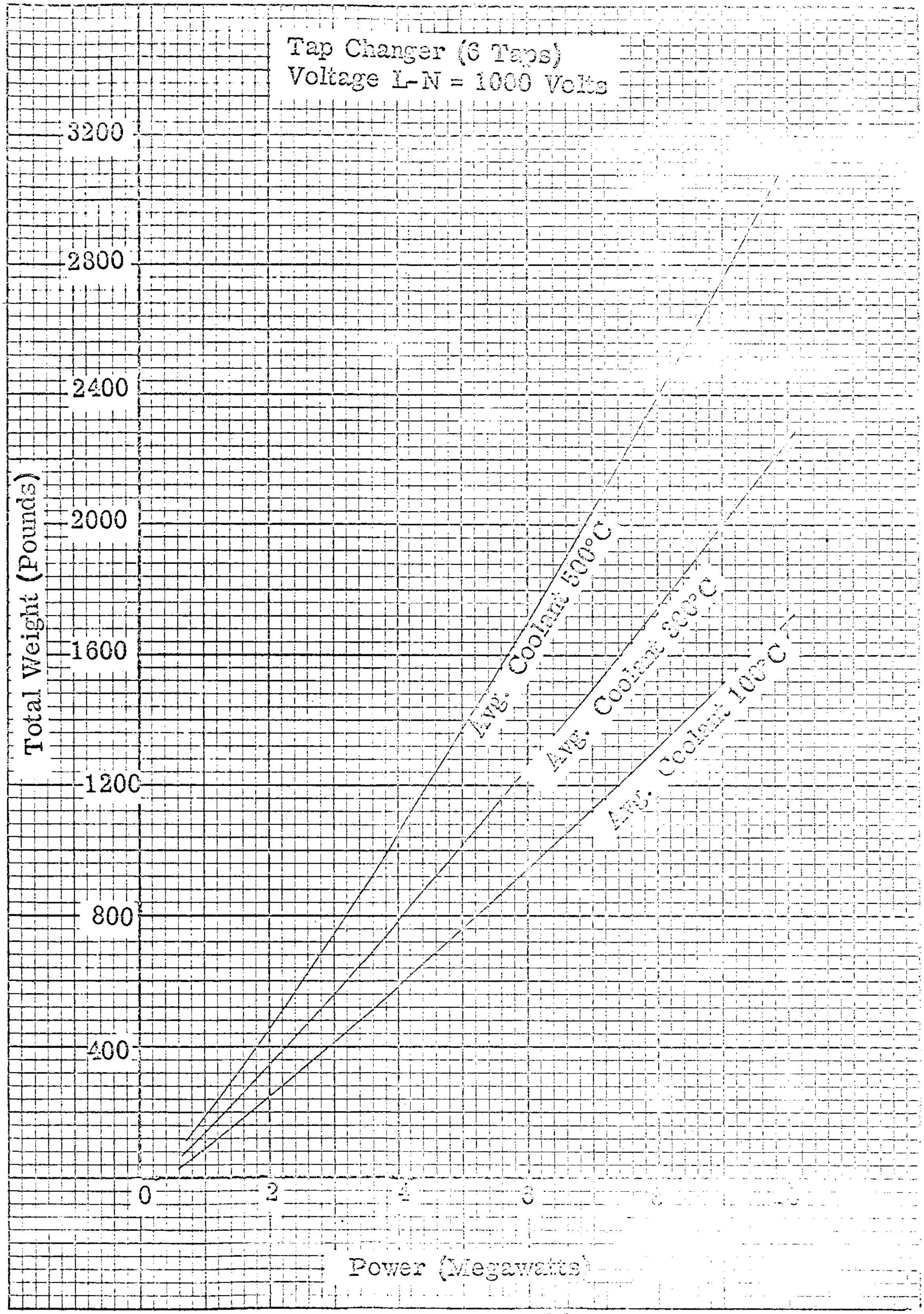


Figure 3. 2. 2-26

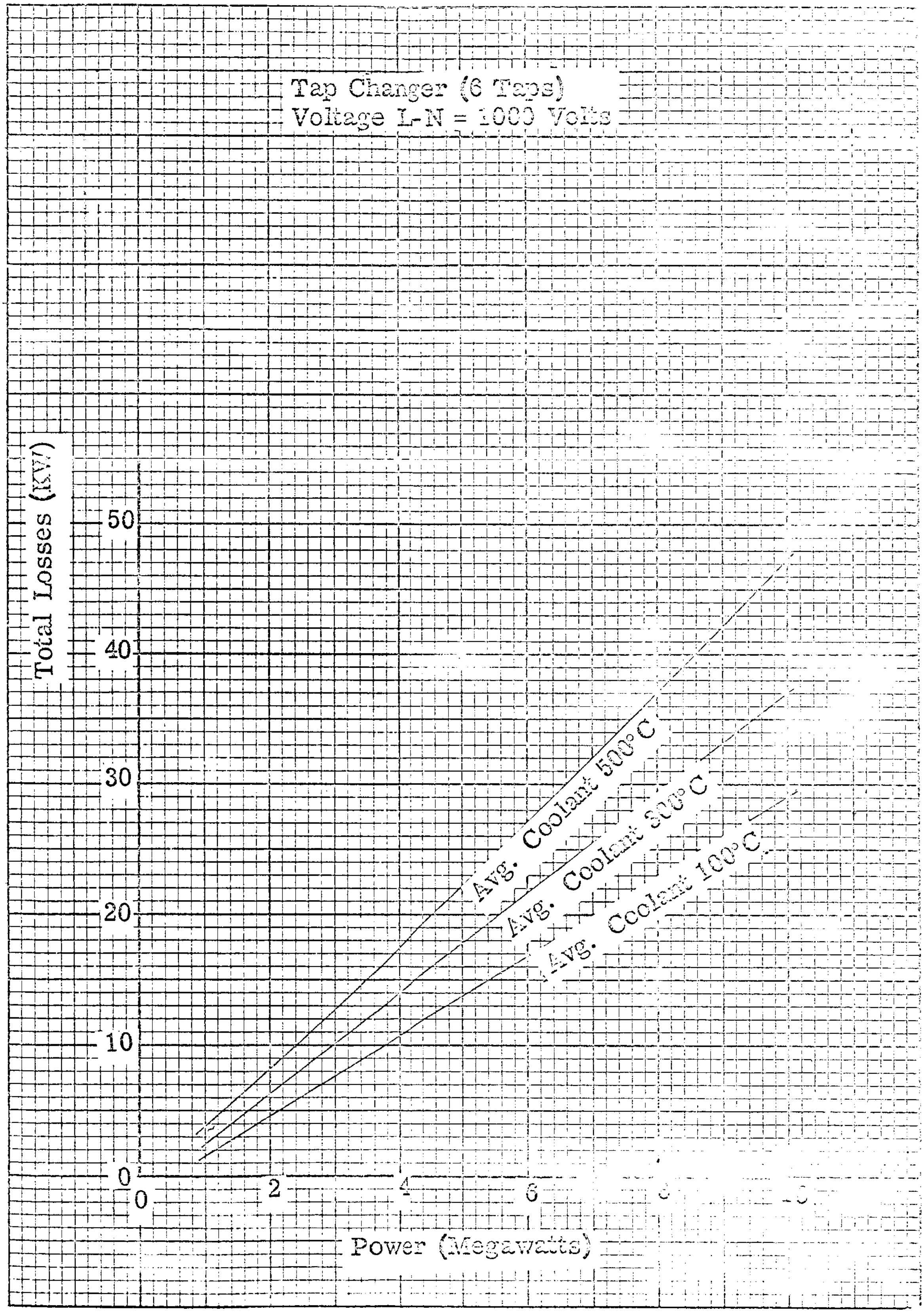


Figure 3. 2. 2-26

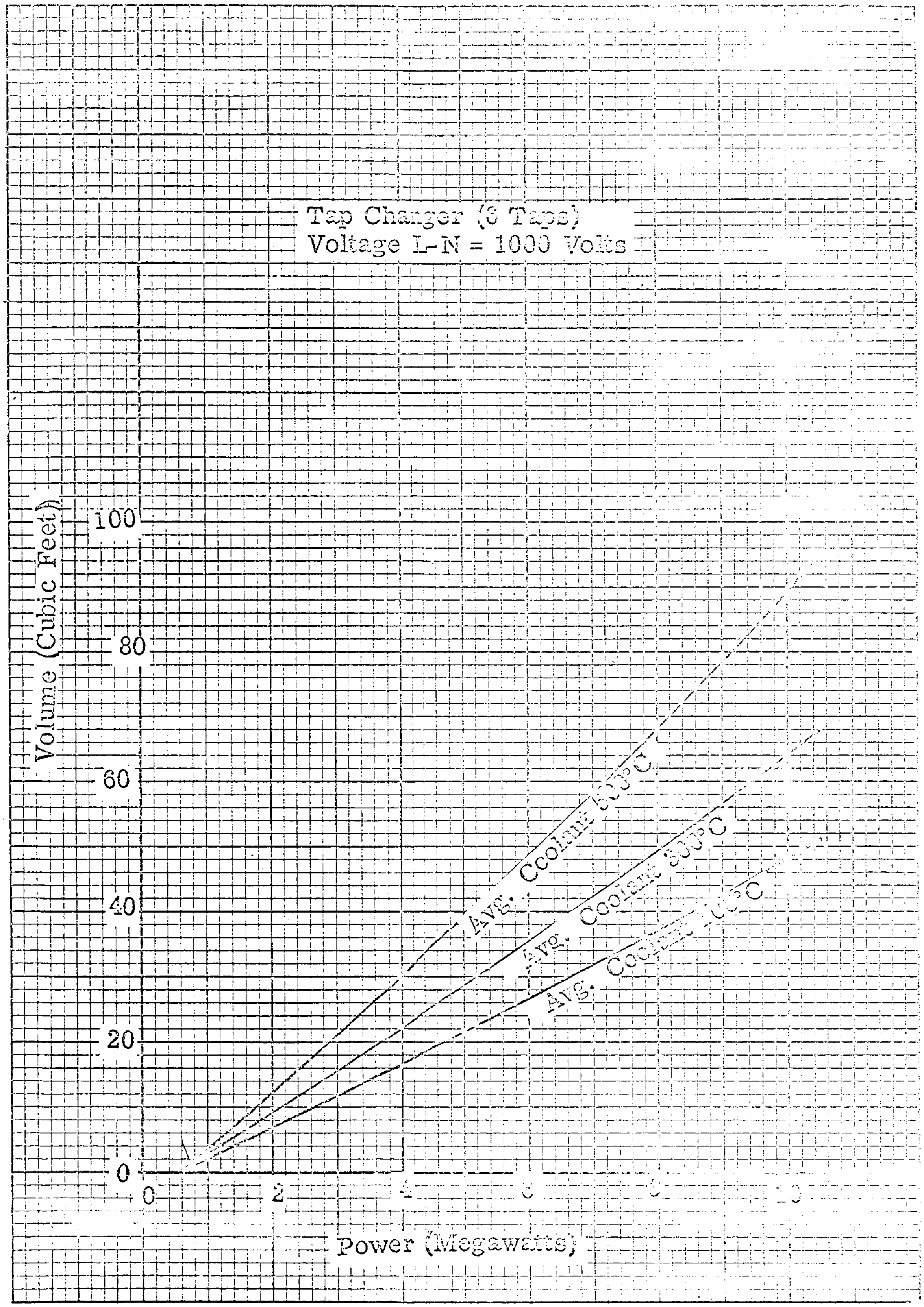


Figure 3.2.2-27

As in the case of the line circuit breaker, the 500/866 volt tap-changer is much heavier than the higher voltage tap-changers. This again is due to the high current levels associated with low voltage systems.

3.2.2.3 Bank Switch

Four-bank and eight-bank switches of the same basic configuration were studied. The configuration used is essentially the same as the tap-changer, i.e. a rotatable inner drum and a fixed outer drum. Again all input and output connections are made to the outer drum.

Figures 3.2.2-28 and 3.2.2-29 are, respectively, schematics of the four-bank and eight-bank switches. The operation of these switches is the same as the tap-changer except for multiple input connection and only two output connections (positive and negative). Rectifier bank connections are shown by dotted lines in the outer drum portion of the schematics.

Figures 3.2.2-30 through 3.2.2-35 show the results of this portion of the study. Input and output voltage levels were chosen by earlier analysis. The data presented here is, therefore, only for 5 KV d-c input and 50 KV d-c output for the eight-bank switch and 10 KV d-c input and 50 KV d-c output for the four-bank switch.

BANK SWITCH SCHEMATIC
(Four Bank)

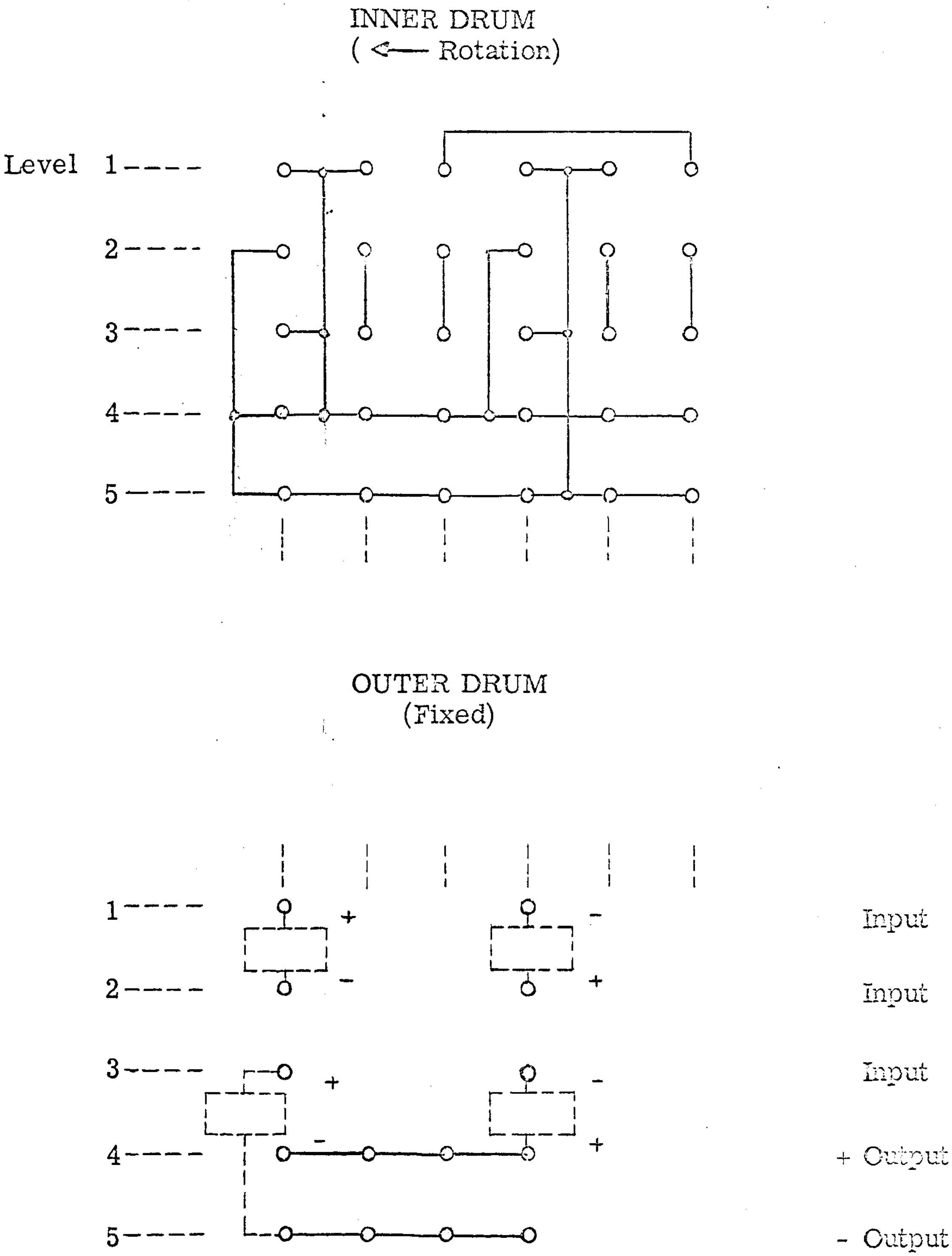


Figure 3. 2. 2-28

BANK SWITCH SCHEMATIC
(Eight Bank)

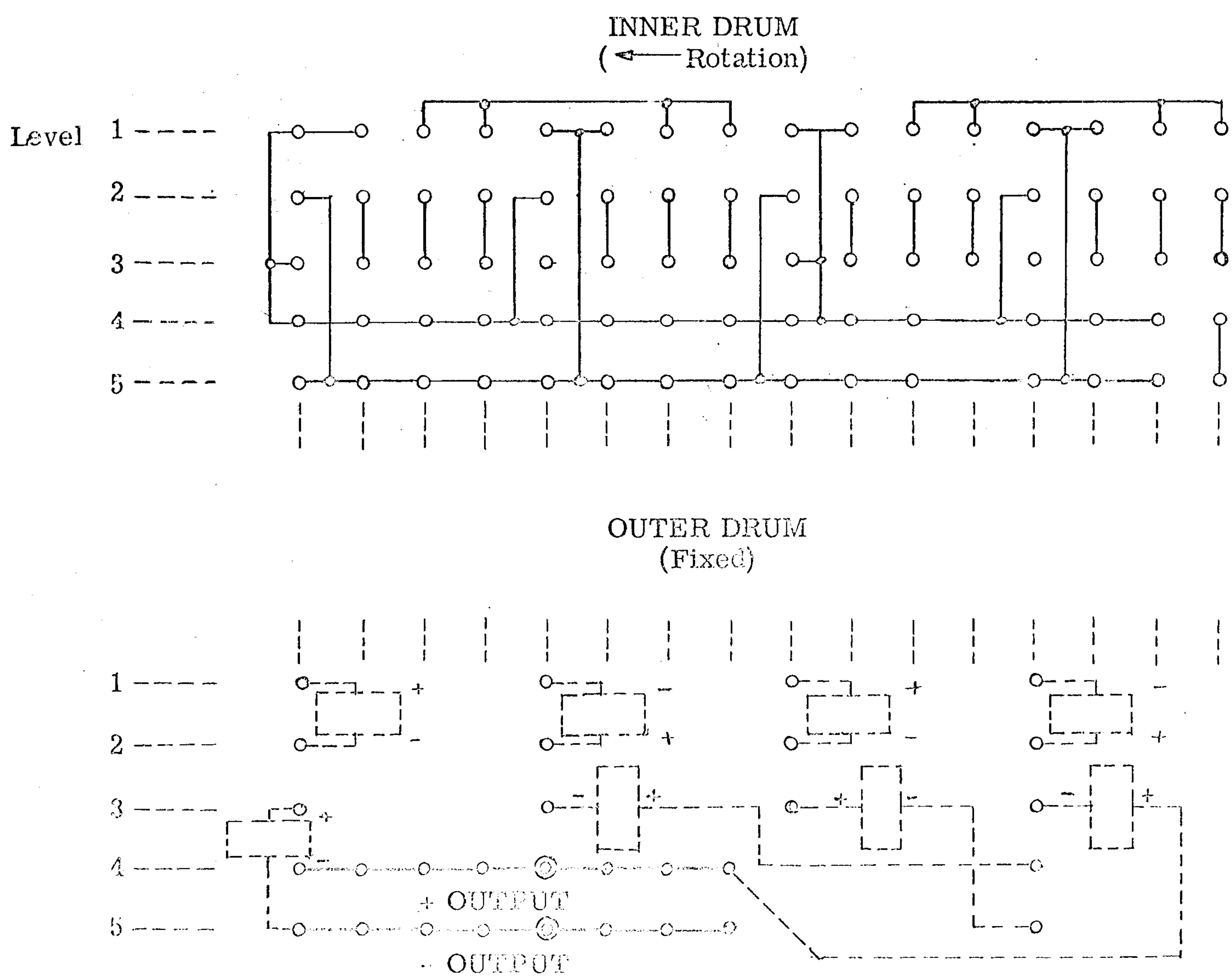


Figure 3. 2. 2-29

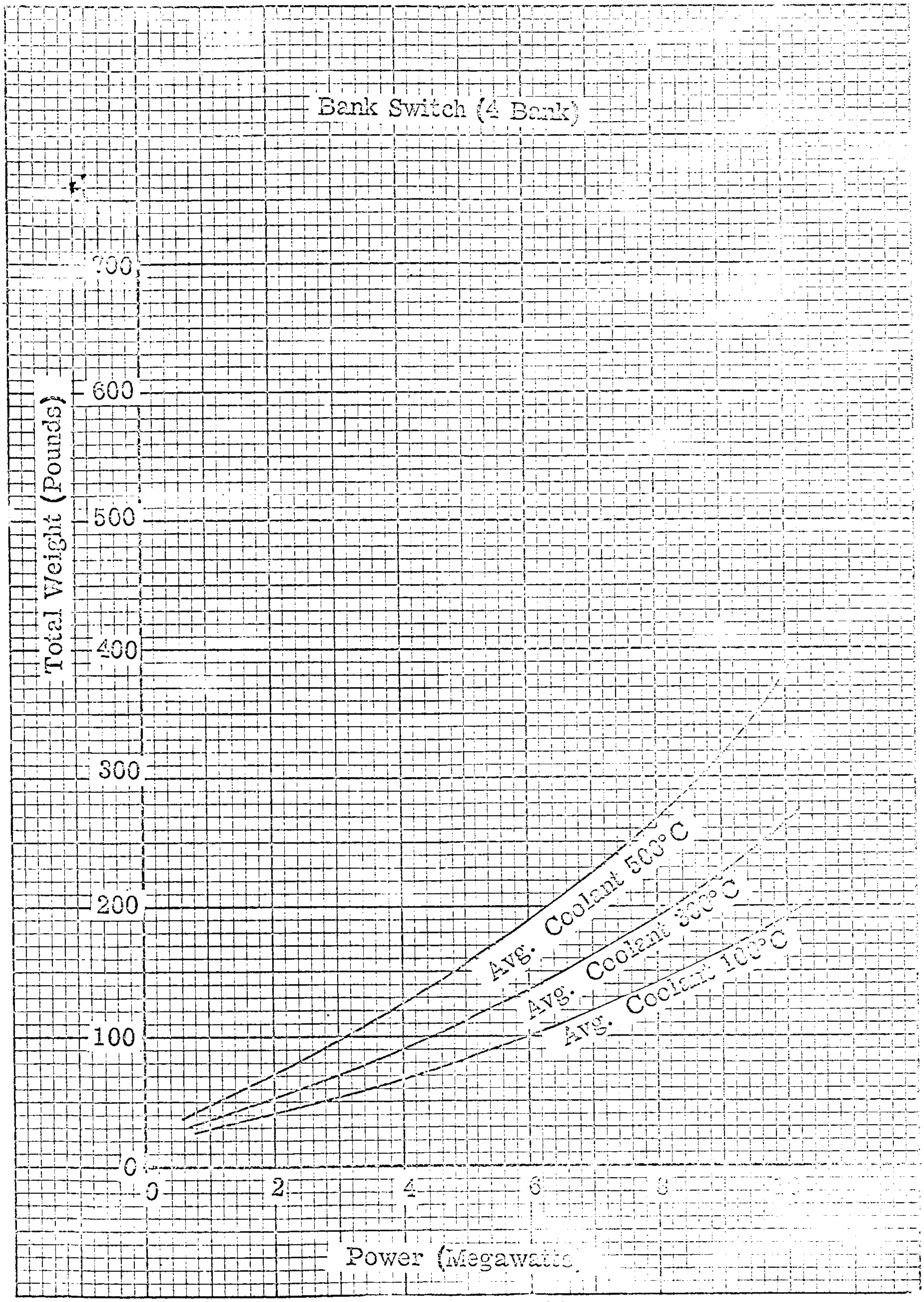


Figure 3.2.2-30

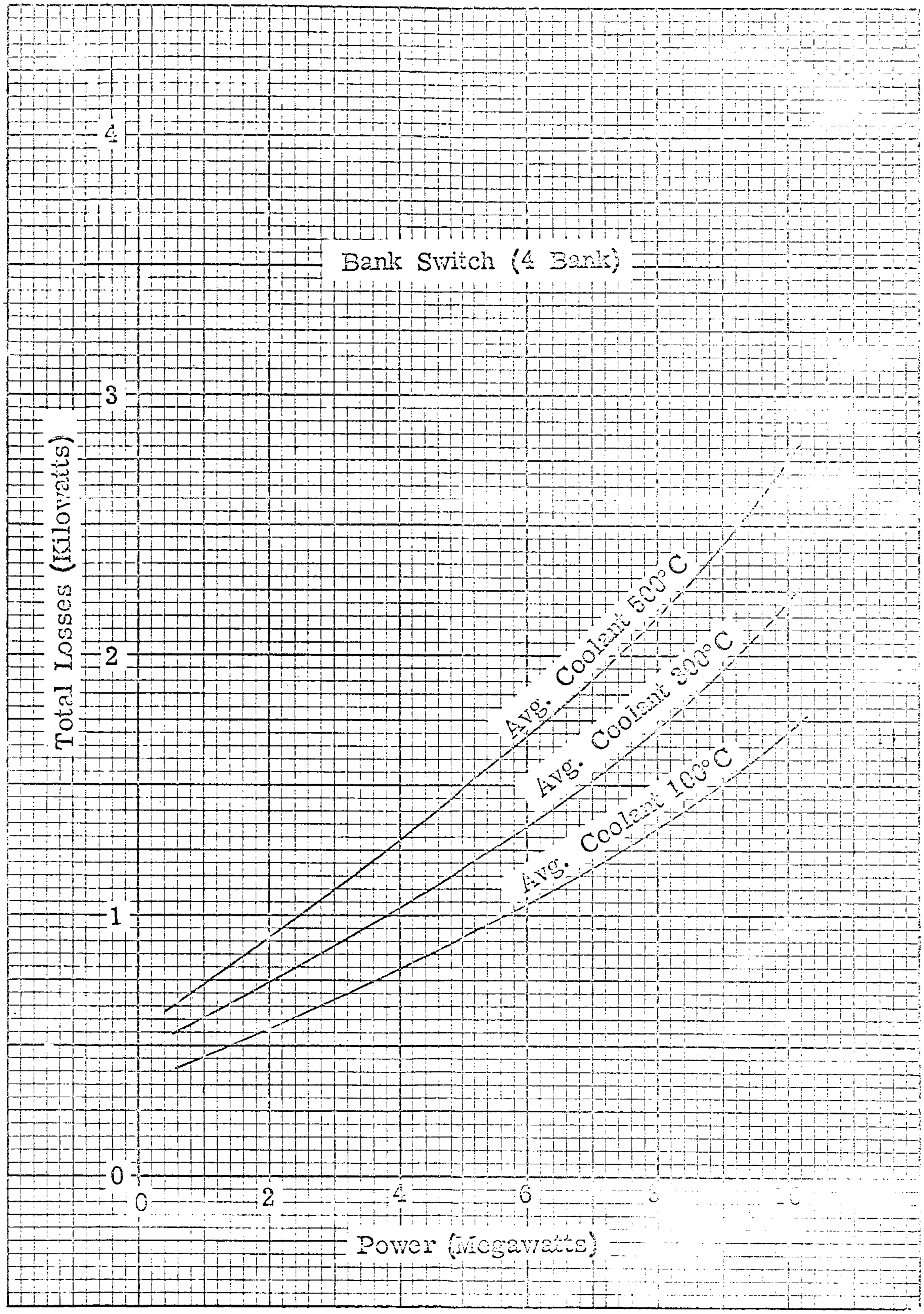


Figure 3. 2. 2-31

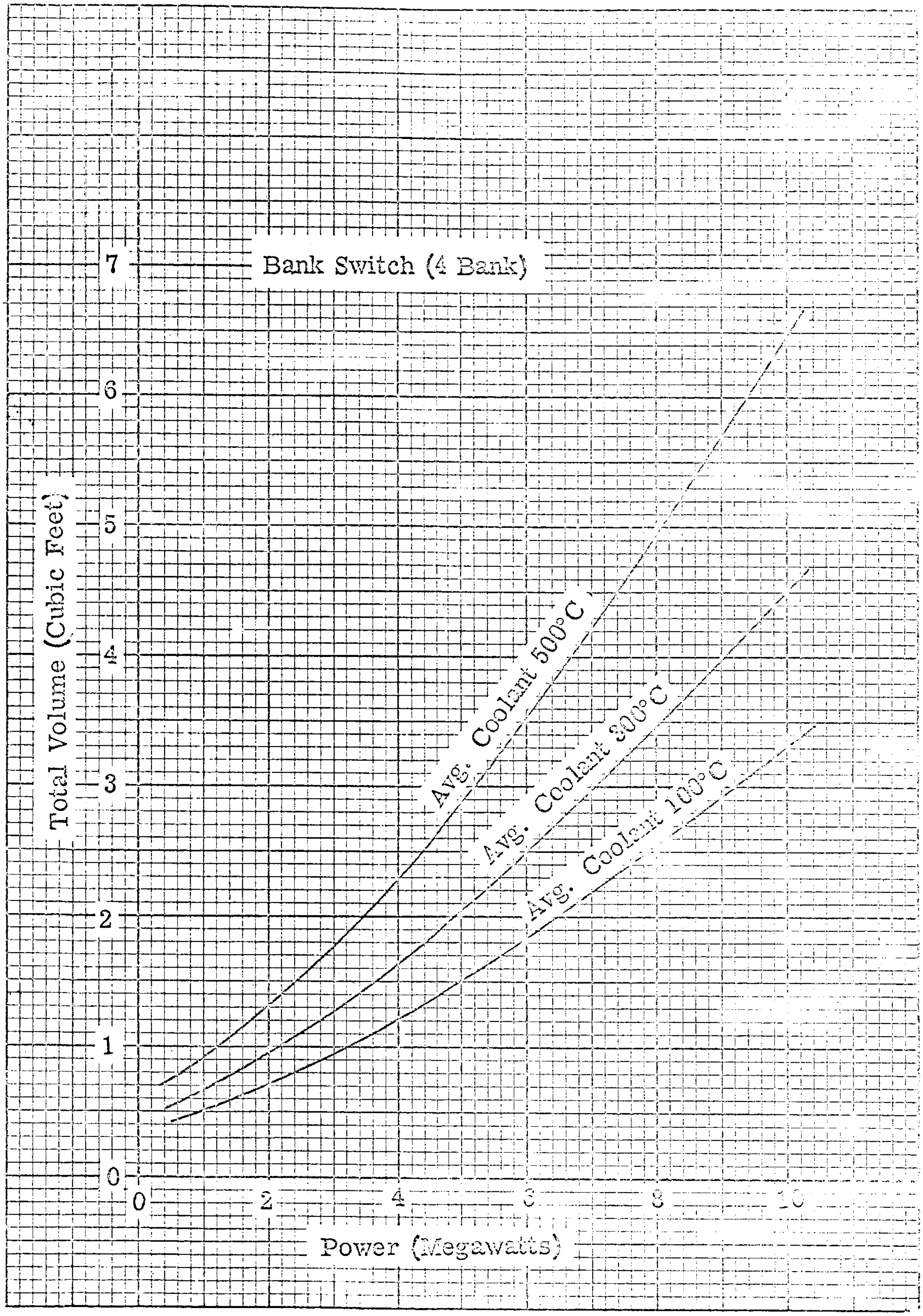


Figure 3. 2. 2-32

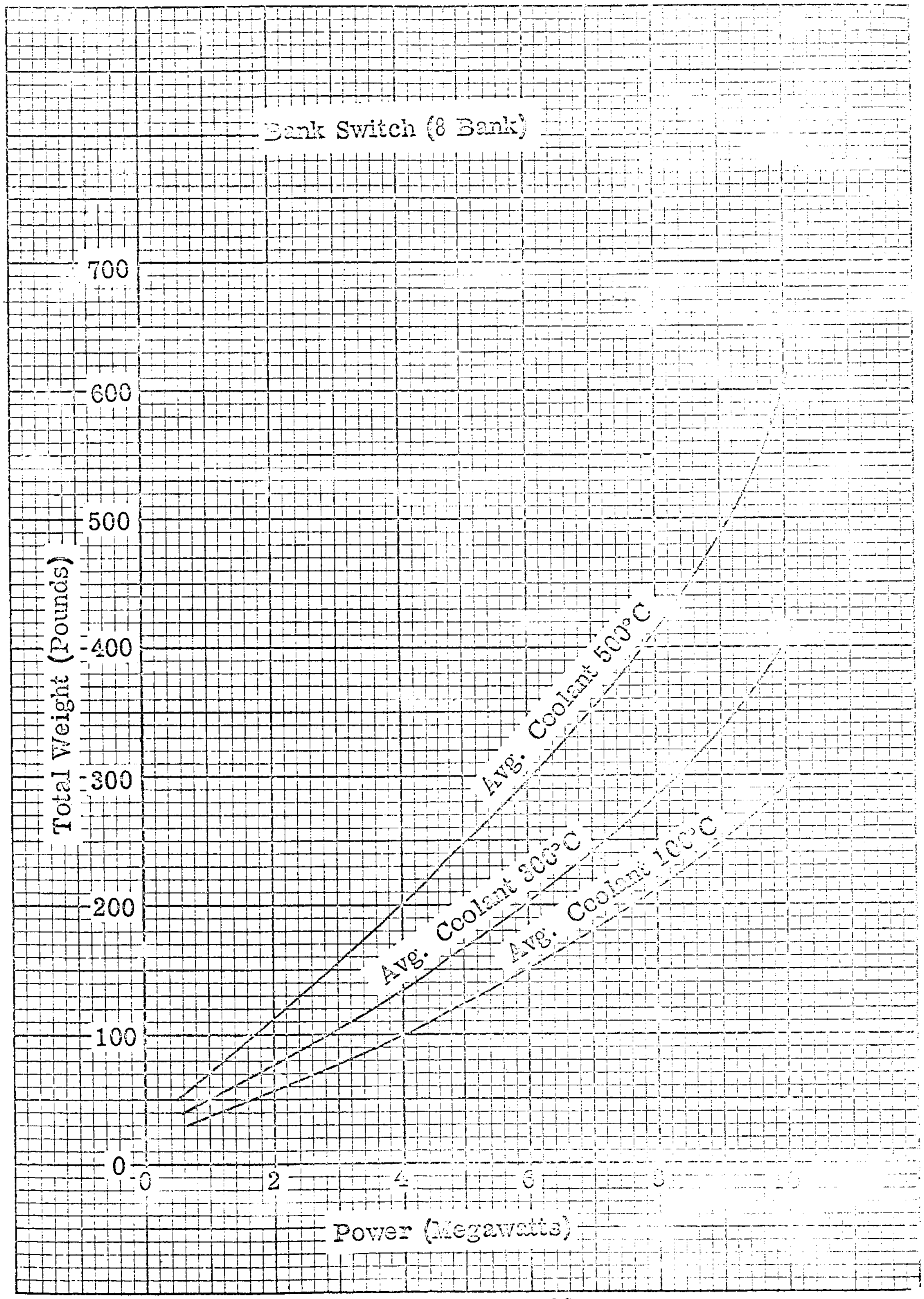


Figure 3. 2. 2-33

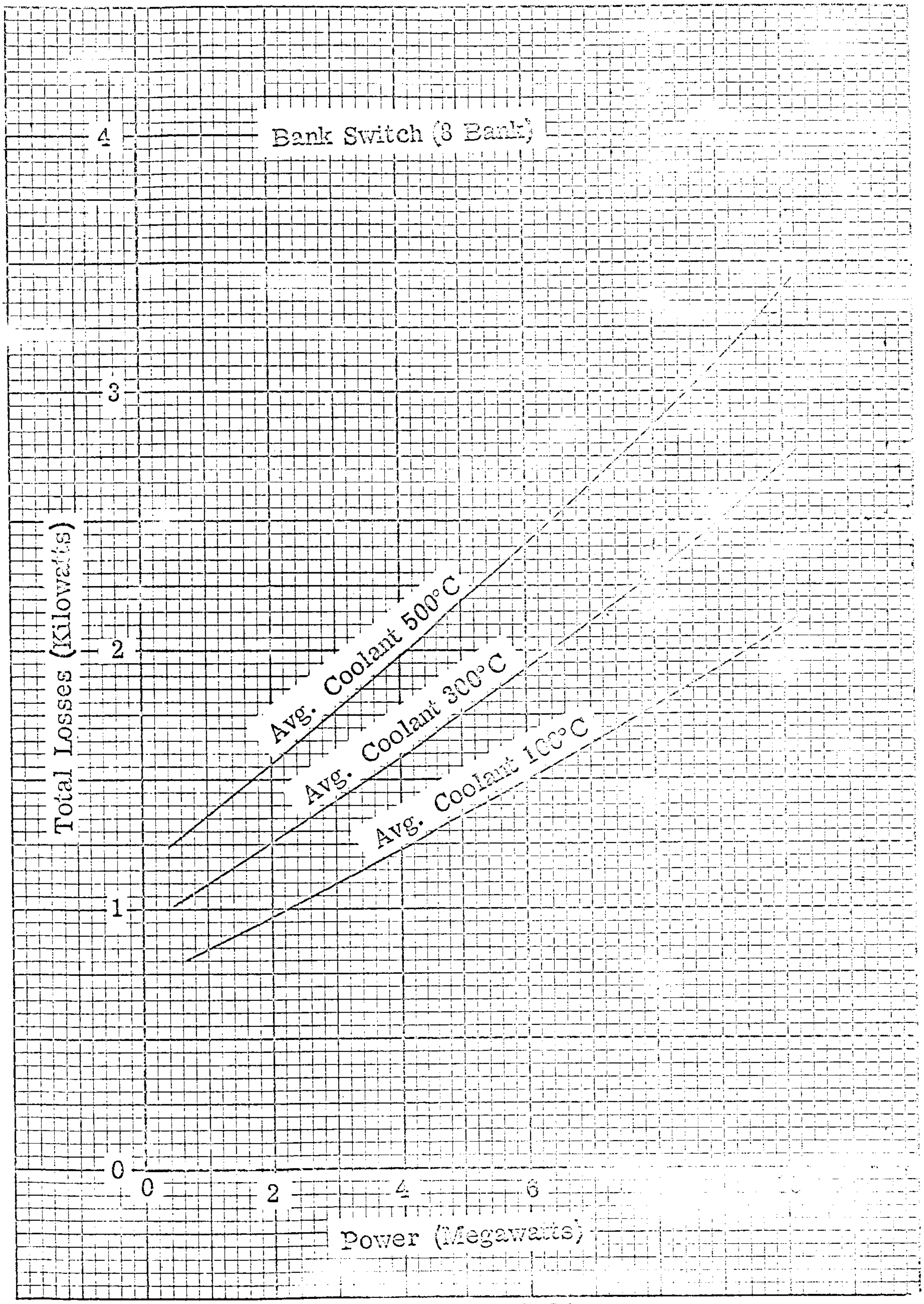


Figure 3. 2. 2-34

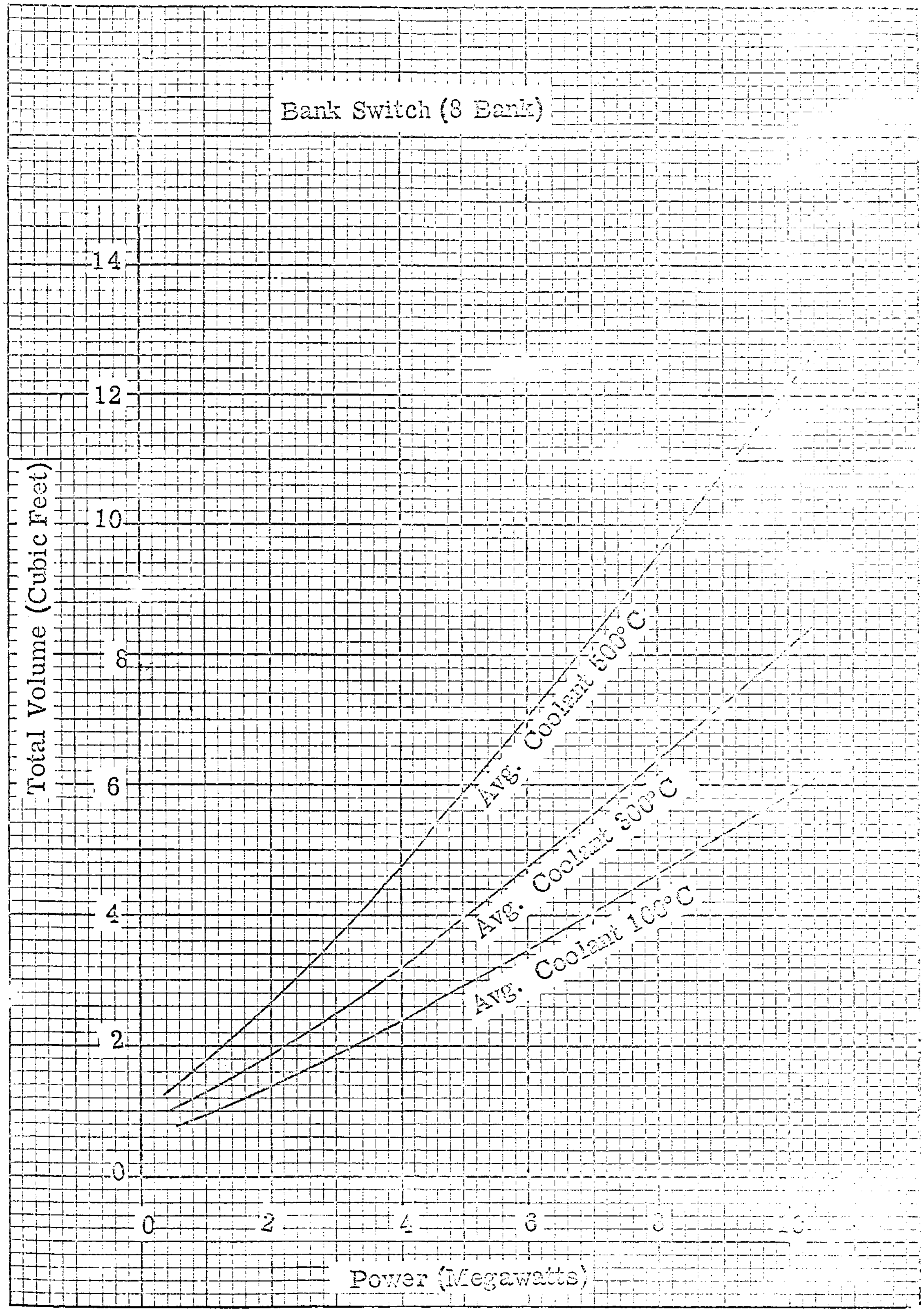


Figure 3. 2. 2-35

3.2.3 Multiple Diode Rectifier Circuits

3.2.3.1 Circuit Connection Considerations

Because the individual diode ratings are not compatible with system requirements, diodes must be connected in series and/or in parallel. The following discussion considers the effect and limitation for these two types of connections.

Diodes in Series

The use of diodes in some high-voltage power rectifier applications requires the use of rectifier elements in series to form the equivalent of a single rectifier device. The use of conventional converter circuits can then be applied to the resulting rectifier stacks or columns. To obtain the voltage capability to withstand the peak inverse voltage (PIV) of a system it is necessary to provide a positive means of uniform voltage distribution across the individual diodes. Diodes, which have their reverse characteristics matched, have operated successfully in series without forced voltage balancing. Because the recovery time may differ from diode to diode; there is some question, however, as to the transient-voltage division during load switching. Because the diode reverse characteristics vary widely, it is possible for several unmatched diodes in a series string to attempt to support the inverse voltage such that the dielectric property of the rectifier device is exceeded. Forced voltage division for diodes in series may be accomplished by shunting each diode with a capacitor - resistor network to compensate for the system parameters which would otherwise destroy the rectifier assembly. The value of the resistors combined with the capacitive reactance of the shunting capacitors provide a sufficiently low value of shunting impedance to insure uniform voltage division under steady-state and transient voltage conditions. The capacitors, which are primarily designed to off-set the effect of the distributed capacitance in the system, offer the additional effect of reducing uneven voltage distribution resulting from the difference in diode recovery time.

Because diodes can withstand greater unbalance than capacitors, the steady-state voltage division across the capacitor must be controlled within closer limits for greatest reliability. The shunting resistors used to force uniform voltage division across the basic diode of a rectifier assembly also serve to keep uniform voltage across the shunting capacitors. Maintaining the peak recurrent voltage across the capacitors within a specified percentage of the capacitors d-c working voltage provides long capacitor life preventing catastrophic system failure.

Diodes in Parallel

To provide the required current capacity in some high power rectifier systems it is necessary to parallel diodes. The low regulation characteristics of rectifying elements require a positive means of current distribution to prevent overloading individual diodes. Proper current division can be obtained by matching the forward diode characteristics, by the addition of series resistance or reactance, by the use of balancing transformers, or by separate transformer windings. For this application, separate transformer windings proved to be the most advantageous.

Reliability

Reliability is normally defined as the ability of a device to satisfactorily perform the specific function for which it was intended. Many confuse system reliability with component reliability. In some cases, this may be true but it cannot be generally accepted as the final word. System reliability is not necessarily assured by simply selecting diodes, resistors, and capacitors to meet the requirements of military standards. Individual components functioning in circuits for which they were intended would prove the reliability of the basic components; however, in dealing with high voltage assemblies, the reliability of the components is not the complete criteria necessary in establishing system reliability. System reliability is an intergrated function governed by the manufacturer's selection of components associated with the particular characteristics which are pertinent to the applied assembly.

A parameter of particular concern for diodes in series is the hole-storage effect, more commonly known as the diode recovery time. The effect of this parameter may go undetected in rectifier applications that normally required to commutate forward current and block reverse voltage in elementary circuits employing one or two diodes in series. For applications requiring many diodes in series, this becomes one of the governing parameters.

In rectifier applications it is necessary to consider the fault current requirements of the system. The magnitude and duration of overload and fault currents dictate the diode type to be used. In order to supply fault current, the diodes do not operate near their designed junction temperature and PIV. If rectifiers were to operate at their maximum design rating, they would have insufficient capacity to handle short circuit currents. Because of the reduced diode-junction temperature, a reduction in percent diode failure can be obtained.

The PIV of the basic diode is determined by considering the possible unbalance in voltage distribution in the series rectifier string. Tolerances of the shunt resistors and capacitors, transient overvoltages, distributed capacitance to ground, and failure of the basic diode or shunt capacitors cause unequal voltage distribution within the rectifier stack. A voltage factor of 2.5 of the system voltage rating is normally satisfactory for high voltage rectifier assemblies to compensate for unbalanced peak inverse diode voltages.

The proper application of the basic diodes and associated shunt components to a high voltage rectifier assembly will provide a system where a diode or capacitor failure is possible and system integrity can still be maintained.

Corona

In electrical systems of 30,000 volts or more, in a gaseous media, a phenomena known as corona is likely to be encountered. Corona is an ionization of the gaseous media caused by over voltage stress from high potential gradients emanating from sharp edges. To counteract this condition mechanical attachments can be adapted to the rectifier stacks.

3.2.3.2 Silicon-Diode, Rectifier-Circuit Parametric Data

Electrical System

The basic transformation circuit considered in the rectifier circuit parametric study is the Wye, 6-Phase, Delta, Double Way (Bridge). This configuration, as determined in the First Quarter Report, provided an overall rectifier system with the least number of diodes and highest rectifier efficiency. This part of the study considers the diodes and voltage balancing components. The transformer parametric study is presented as a separate write-up.

Tables 3.2.3-1 through 3.2.3-6 list component quantity, size, weight, and power losses for a 4-bank and 8-bank silicon-rectifier system capable of providing 1, 5, and 10-megawatts at system direct current voltages of 5, 10, 20, 40, and 50 kilovolts.

A voltage factor of 2.5 of the normal diode peak inverse voltage requirement established the diode quantity per rectifier bridge.

The basic silicon diode selected for the 10-megawatt, 4-rectifier-bank system has the greatest power conducting capability presently available. This diode meets the normal 10-megawatt system current requirement in the range of 5 to 20 kilovolts and provides short circuit capability when paralleled. The use of two permanently paralleled rectifier bridges and the associated transformer secondary windings do not alter the basic bank switching arrangement. With continued advancement in current capabilities of single diode units, with a forecast of 500 ampere devices within 5 years, a 4-rectifier bank without paralleled diodes would furnish the required power.

TABLE 3.2.3-1

10 Megawatt - 8 Rectifier Bank Silicon Diode System

	D-C Bus Volts	5 KV	10 KV	20 KV	40 KV	50 KV
Diode	Rect. Bank Condition	8 Par. 1 Ser.	4 Par. 2 Ser.	2 Par. 4 Ser.	8 Ser.	8 Ser.
	Load D-C Amps	2000	1000	500	250	200
	Amps/3 Phase Bridge	250	250	250	250	200
	Amps/Bridge Leg Peak Amps Avg. Amps	 250 83.3	 250 83.3	 250 83.3	 250 83.3	 200 66.7
	Diode PIV	1200	1200	1200	1200	1200
	Diodes/3 Phase Bridge	132	132	132	132	132
	Total No. Diodes	1056	1056	1056	1056	1056
	Diode Type	JEDEC 1N3170 Except 1200 PIV	JEDEC 1N3170 Except 1200 PIV	JEDEC 1N3170 Except 1200 PIV	JEDEC 1N3170 Except 1200 PIV	JEDEC 1N3170 Except 1200 PIV
	Watts Loss/Diode	97	97	97	97	75
	Total Diode Loss	102,432	102,432	102,432	102,432	79,200
	PIV, Multip. Factor	5.02	2.51 5.02	2.51 5.02	2.51 5.02	4.02
	Total Diode Wt. (#)	528	528	528	528	528
	Total Diode Vol. (IN^3)	5870	5870	5870	5870	5870
Resistor	Shunt Res. (Ohms)	20K	20K	20K	20K	20K
	Watts Loss/ Res.	1.31	1.31	1.31	1.31	2.04
	Total Qty. Res.	1056	1056	1056	10[illegible]	1056
	Total Res. Watts	1395	1395	1395	13[illegible]	2150
	Total Res. Wt. (#)	12.5	12.5	12.5	12.[illegible]	12.5
	Dimensions	1-13/16" L 13/32 " D	1-13/16" L 13/32" D	1-13/16" L 13/32" D	1-13/16" L 13/32" D	1-13/16" L 13/32" D
Capacitor	Shunt Cap. (ufd)	0.1	0.1	0.1	0.1	0.1
	Watts Loss/Cap.	0.163	0.163	0.163	0.[illegible]	0.255
	Total Qty. Cap	1056	1056	1056	[illegible]	1056
	Total Cap. Watts	172	172	172	[illegible]	269
	Total Cap. Wt. (#)	105	105	105	[illegible]	105
	Dimensions	1.875" L .750" D	1.875" L .750" D	1.875" L .750" D	1.[illegible]" L .7[illegible]" D	1.875" L .750" D
	Total Watts Loss	103,999	103,999	103,999	103,9[illegible]	81,619

TABLE 3. 2. 3-2

5 Megawatt - 8 Rectifier Bank Silicon Diode System

	D-C Bus Volts	5 KV	10 KV	20 KV	40 KV	50 KV
Diode	Rect. Bank Condition	8 Par. 1 Ser.	4 Par. 2 Ser.	2 Par. 4 Ser.	8 Ser.	8 Ser.
	Load D-C Amps	1000	500	250	125	100
	Amps/3 Phase Bridge	125	125	125	125	100
	Amps/Bridge Leg Peak Amps Avg. Amps	 125 41.7	 125 41.7	 125 41.7	 125 41.7	 100 33.3
	Diode PIV	1200	1200	1200	1200	1200
	Diodes/3 Phase Bridge	132	132	132	132	132
	Total No. Diodes	1056	1056	1056	1056	1056
	Diode Type	JEDEC 1N3170 Except 1200 PIV	JEDEC 1N3170 Excpet 1200 PIV	JEDEC 1N3170 Except 1200 PIV	JEDEC 1N3170 Except 1200 PIV	JEDEC 1N3170 Except 1200 PIV
	Watts Loss/Diode	42.6	42.6	42.6	42.6	32.6
	Total Diode Loss	45,000	45,000	45,000	45,000	34,400
	PIV, Multip. Factor	5.02	2.51 5.02	2.51 5.02	2.51 5.02	4.02
	Total Diode Wt. (#)	528	528	528	528	528
	Total Diode Vol. (IN^3)	5870	5870	5870	5870	5870
Resistor	Shunt Res. (Ohms)	20 K	20 K	20 K	20 K	20 K
	Watts Loss/Res.	1.31	1.31	1.31	1.31	2.04
	Total Qty. Res.	1056	1056	1056	1056	1056
	Total Res. Watts	1395	1395	1395	1395	1395
	Total Res. Wt. (#)	12.5	12.5	12.5	12.5	12.5
	Dimensions	1-13/16" L 13/32" D	1-13/16" L 13/32" D	1-13/16" L 13/32" D	1-13/16" L 13/32 " D	1-13/16" L 13/32" D
Capacitor	Shunt Cap. (ufd)	0.1	0.1	0.1	0.1	0.1
	Watts Loss/Cap.	0.163	0.163	0.163	0.163	0.255
	Total Qty. Cap.	1056	1056	1056	1056	1056
	Total Cap. Watts	172	172	172	172	269
	Total Cap. Wt (#)	105	105	105	105	105
	Dimensions	1.875" L .750" D	1.875" L .750" D	1.875" L .750" D	1.875" L .750" D	1.875" L .750" D
	Total Watts Loss	46,567	46,567	46,567	46,567	36,819

TABLE 3. 2. 3-3

1 Megawatt - 8 Rectifier Bank Silicon Diode System

	D-C Bus Volts	5 KV	10 KV	20 KV	40 KV	50 KV
Diode	Rect. Bank Condition	8 Par. 1 Ser.	4 Par. 2 Ser.	2 Par. 4 Ser.	8 Ser.	8 Ser.
	Load D-C Amps	200	100	50	25	20
	Amps/3 Phase Bridge	25	25	25	25	20
	Amps/Bridge Leg Peak Amps Avg. Amps	 25 8.33	 25 8.33	 25 8.33	 25 8.33	 20 6.67
	Diode PIV	800	800	800	800	800
	Diodes/3 Phase Bridge	198	198	198	198	198
	Total No. Diodes	1584	1584	1584	1584	1584
	Diode Type	JEDEC 1N1190 Except 800 PIV	JEDEC 1N1190 Except 800 PIV	JEDEC 1N1190 Except 800 PIV	JEDEC 1N1190 Except 800 PIV	JEDEC 1N1190 Except 800 PIV
	Watts Loss/Diode	8.75	8.75	8.75	8.75	6.65
	Total Diode Loss	13,870	13,870	13,870	13,870	10,520
	PIV, Multip. Factor	5.02	2.51 5.02	2.51 5.02	2.51 5.02	4.02
	Total Diode Wt. (#)	64.3	64.3	64.3	64.3	64.3
	Total Diode Vol. (IN^3)	1064	1065	1065	1065	1065
Resistor	Shunt Res. (Ohms)	40 K	40 K	40 K	40 K	40 K
	Watts Loss/Res.	0.292	0.292	0.292	0.292	.449
	Total Qty. Res.	1584	1584	1584	1584	1584
	Total Res. Watts	463	463	463	463	712
	Total Res. Wt. (#)	8.9	8.9	8.9	8.9	8.9
	Dimensions	7/8" L 5/16" D	7/8" L 5/16" D	7/8" L 5/16" D	7/8" L 5/16" D	7/8" L 5/16" D
Capacitor	Shunt Cap. (ufd)	.047	.047	.047	.047	.047
	Watts Loss/Cap	.0342	.0342	.0342	.0342	[illegible]
	Total Qty. Cap.	1584	1584	1584	1584	[illegible]
	Total Cap. Watts	54.3	54.3	54.3	54.3	[illegible]
	Total Cap. Wt. (#)	125.5	125.5	125.5	125.5	[illegible]
	Dimensions	1.875" L .670" D	1.875" L .670" D	1.875" L .670" D	1.875" L .670" D	1.875" L .670" D
	Total Watts Loss	14,387	14,387	14,387	[illegible]	11,316

TABLE 3. 2. 3-4

10 Megawatt - 4 Rectifier Bank Silicon Diode System

	D-C Bus Volts	5 KV	10 KV	20 KV	40 KV	50 KV
Diode	Rect. Bank Condition	8 Par. 1 Ser.	4 Par. 2 Ser.	2 Par. 4 Ser.	2 Par. 4 Ser.	2 Par. 4 Ser.
	Load D-C Amps	2000	1000	500	250	200
	Amps/3 Phase Bridge	250	250	250	125	100
	Amps/Bridge Leg Peak Amps Avg. Amps	 250 83.3	 250 83.3	 250 83.3	 125 41.7	 100 33.3
	Diode PIV	1200	1200	1200	1200	1200
	Diodes/3 Phase Bridge	168	168	168	168	168
	Total No. Diodes	1344	1344	1344	1344	1344
	Diode Type	JEDEC 1N3170 Except 1200 PIV	JEDEC 1N3170 Except 1209 PIV	JEDEC 1N3170 Except 1200 PIV	JEDEC 1N3170 Except 1200 PIV	JEDEC 1N3170 Except 1200 PIV
	Watts Loss/Diode	97	97	97	42.6	32.6
	Total Diode Loss	130,368	130,368	130,368	57,300	43,800
	PIV, Multip. Factor	6.4	3.2 6.4	3.2 6.4	3.2	2.51
	Total Diode Wt. (#)	672	672	672	672	672
	Total Diode Vol (IN^3)	7480	7480	7480	7480	7480
Resistor	Shunt Res. (Ohms)	20 K	20 K	20 K	20 K	20 K
	Watts Loss/Res.	.806	.806	.806	3.22	5.0
	Total Qty. Res.	1344	1344	1344	1344	1344
	Total Res. Watts	1084	1084	1084	4330	6730
	Total Res. Wt. (#)	15.9	15.9	15.9	15.9	15.9
	Dimensions	1-13/16" L 13/32" D	1-13/16" L 13/32" D	1-13/16" L 13/32" D	1-13/16" L 13/32" D	1-13/16" L 13/32" D
Capacitor	Shunt Cap. (ufd)	0.1	0.1	0.1	0.1	0.1
	Watts Loss/Cap.	.1005	.1005	.1005	[illegible]	.625
	Total Qty. Cap.	1344	1344	1344	[illegible]	1344
	Total Cap. Watts	135	135	135	[illegible]	840
	Total Cap Wt. (#)	133	133	133	[illegible]	133
	Dimensions	1.875" L .750" D	1.875" L .750" D	1.875" L .750" D	1.875" L .750" D	1.875" L .750" D
	Total Watts Loss	131,587	131,587	131,587	62,173	51,370

TABLE 3. 2. 3-5

5 Megawatt - 4 Rectifier Bank Silicone Diode System

	D-C Bus Volts	5 KV	10 KV	20 KV	40 KV	50 KV
Diode	Rect. Bank Condition	4 Par. 1 Ser.	2 Par. 2 Ser.	4 Ser.	4 Ser.	4 Ser.
	Load D-C Amps	1000	500	250	125	100
	Amps/3 Phase Bridge	250	250	250	125	100
	Amps/Bridge Leg Peak Amps Avg. Amps	 250 83.3	 250 83.3	 250 83.3	 125 41.7	 100 33.3
	Diode PIV	1200	1200	1200	1200	1200
	Diodes/3 Phase Bridge	168	168	168	168	168
	Total No. Diodes	672	672	672	672	672
	Diode Type	JEDEC 1N3170 Except 1200 PIV	JEDEC 1N3170 Except 1200 PIV	JEDEC 1N3170 Except 1200 PIV	JEDEC 1N3170 Except 1200 PIV	JEDEC 1N3170 Except 1200 PIV
	Watts Loss/Diode	97	97	97	42.6	32.6
	Total Diode Loss	65,200	65,200	65,200	28,600	21,900
	PIV, Multip. Factor	6.4	3.2 6.4	3.2 6.4	3.2	2.51
	Total Diode Wt. (#)	336	336	336	336	336
	Total Diode Vol. (IN^3)	3740	3740	3740	3740	3740
Resistor	Shunt Res. (Ohms)	20 K	20 K	20 K	20 K	20 K
	Watts Loss/Res.	.806	.806	.806	3.22	5.0
	Total Qty. Res.	672	672	672	672	672
	Total Res. Watts	542	542	542	2165	3360
	Total Res. Wt. (#)	7.96	7.96	7.96	7.96	7.96
	Dimensions	1-13/16" L 13/32" D	1-13/16" L 13/32" D	1-13/16" L 13/32" D	1-13/16" L 13/32" D	1-13/16" L 13/32" D
Capacitor	Shunt Cap. (ufd)	0.1	0.1	0.1	0.1	0.1
	Watts Loss/Cap.	.1005	.1005	.1005	.403	.625
	Total Qty. Cap.	672	672	672	672	672
	Total Cap. Watts	67.5	67.5	67.5	27[illegible]	420
	Total Cap. Wt. (#)	66.6	66.6	66.6	66.6	66.6
	Dimensions	1.875" L .750" D	1.875" L .750" D	1.875" L .750" D	1.875" L .750" D	1.875" L .750" D
	Total Watts Loss	65,810	65,810	65,810	31,036	25,030

TABLE 3. 2. 3-6

1 Megawatt - 4 Rectifier Bank Silicon Diode System

	D-C Bus Volts	5 KV	10 KV	20 KV	40 KV	50 KV
Diode	Rect. Bank Condition	4 Par. 1 Ser.	2 Par. 2 Ser.	4 Ser.	4 Ser.	4 Ser.
	Load D-C Amps	200	100	50	25	20
	Amps/3 Phase Bridge	50	50	50	25	20
	Amps/Bridge Leg Peak Amps Avg. Amps	 50 16.67	 50 16.67	 50 16.67	 25 8.3	 20 6.67
	Diode PIV	800	800	800	800	800
	Diodes/3 Phase Bridge	252	252	252	252	252
	Total No. Diodes	1008	1008	1008	1008	1008
	Diode Type	W 300	W 300	W 300	W 300	W 300
	Watts Loss/Diode	17.7	17.7	17.7	8.26	6.56
	Total Diode Loss	17,850	17,850	17,850	8,330	6,510
	PIV, Multip. Factor	6.4	3.2 6.4	3.2 6.4	3.2	2.51
	Total Diode Wt. (#)	189	189	189	189	189
	Total Diode Vol (IN^3)	2380	2380	2380	2380	2380
Resistor	Shunt Res. (Ohms)	20 K	20 K	20 K	20 K	20 K
	Watts Loss/Res.	.357	.357	.357	1.435	2.25
	Total Qty. Res.	1008	1008	1008	1008	1008
	Total Res. Watts	360	360	360	1450	2270
	Total Res. Wt. (#)	5.67	5.67	5.67	5.67	5.67
	Dimensions	7/8" L 5/16" D	7/8" L 5/16" D	7/8" L 5/16" D	7/8" L 5/16" D	7/8" L 5/16" D
Capacitor	Shunt Cap. (mfd)	0.1	0.1	0.1	0.1	0.1
	Watts Loss/Cap.	.0444	.0444	.0444	.157	[illegible]
	Total Qty. Cap.	1008	1008	1008	1008	[illegible]
	Total Cap. Watts	44.8	44.8	44.8	158	[illegible]
	Total Cap. Wt. (#)	100	100	100	100	[illegible]
	Dimensions	1.875" L .750" D	1.875" L .750" D	1.875" L .750" D	1.875" L .750" D	1.875" L .750" D
	Total Watts Loss	18,255	18,255	18,255	9,938	9,00[illegible]

Comparison of rectifier efficiency to the direct current system power and voltage requirements is presented in Figures 3. 2. 3-1 through 3. 2. 3-4 for the 8-bank and 4-bank silicon-rectifier equipment. These efficiency curves include the power losses of the associated capacitors and resistors.

Cooling System

Variation of total weight and volume, required coolant flow, and coolant inlet temperature for the 4-bank and 8-bank rectification systems at 1, 5, and 10-megawatts is presented for both a cold-plate cooling system and a liquid-bath cooling system in Figures 3. 2. 3-5 through 3. 2. 3-8. Monoisopropyl biphenyl (MIPB) is used throughout as a coolant. Coolant flow and inlet temperature curves are based on an assumed coolant temperature rise of 10°C in the system.

In the cold-plate cooling system, diodes are assumed to be mounted on a layer of beryllium oxide insulation, which in turn is fastened to the plate. Coolant flow tubes are either embedded in or brazed directly to the plate. Beryllium oxide insulation is assumed to avoid a large insulation temperature drop between the diode case and the cold plate. Cooling-tube design requirements are based on an assumed convection coefficient of 0. 500 watts/ in^2-°C.

In the liquid bath cooling system, diodes are mounted through conventional insulation to the supporting structure and are completely immersed in coolant, which flows directly over them. A convection coefficient of 0. 250 watts/ in^2-°C is assumed.

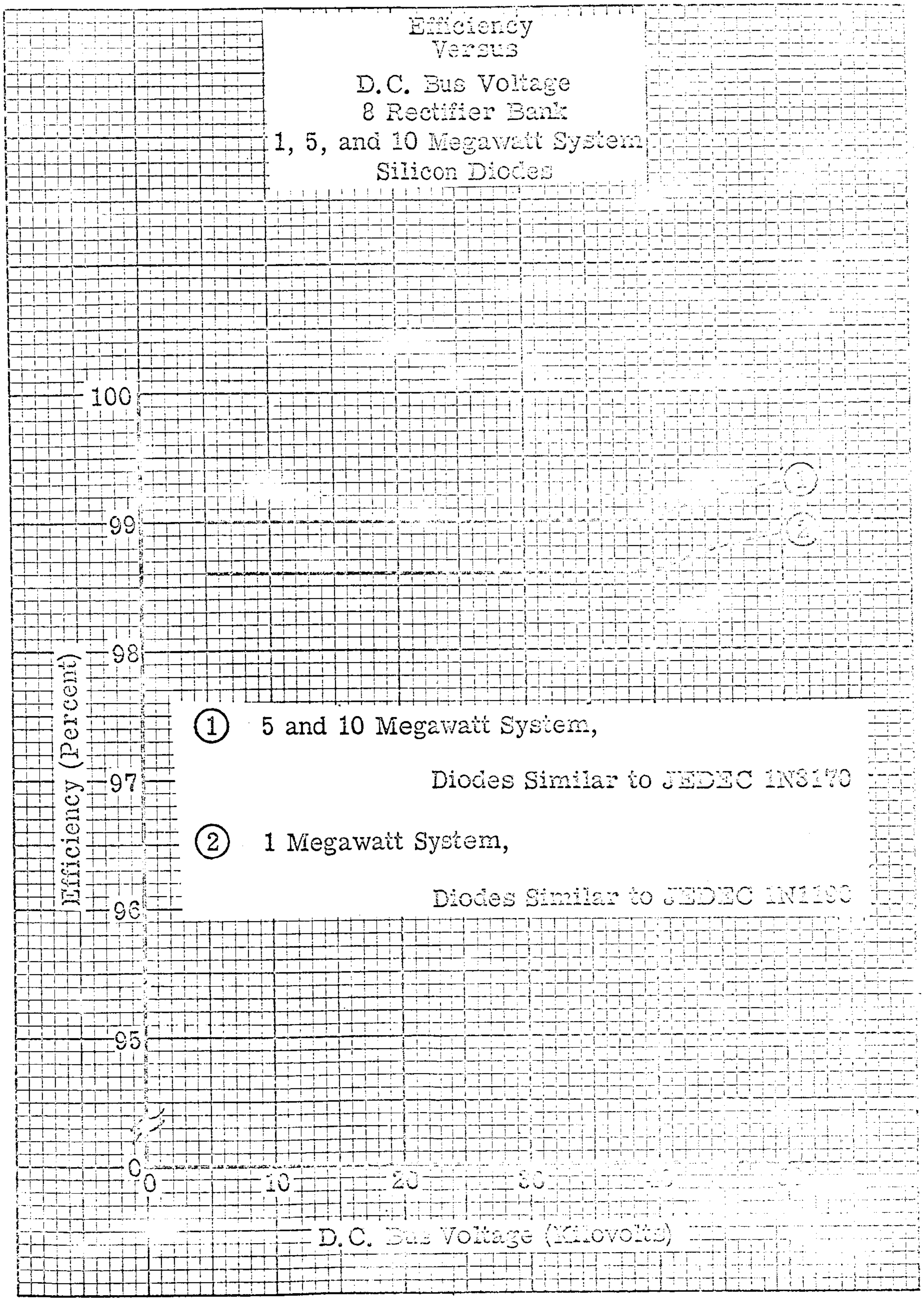
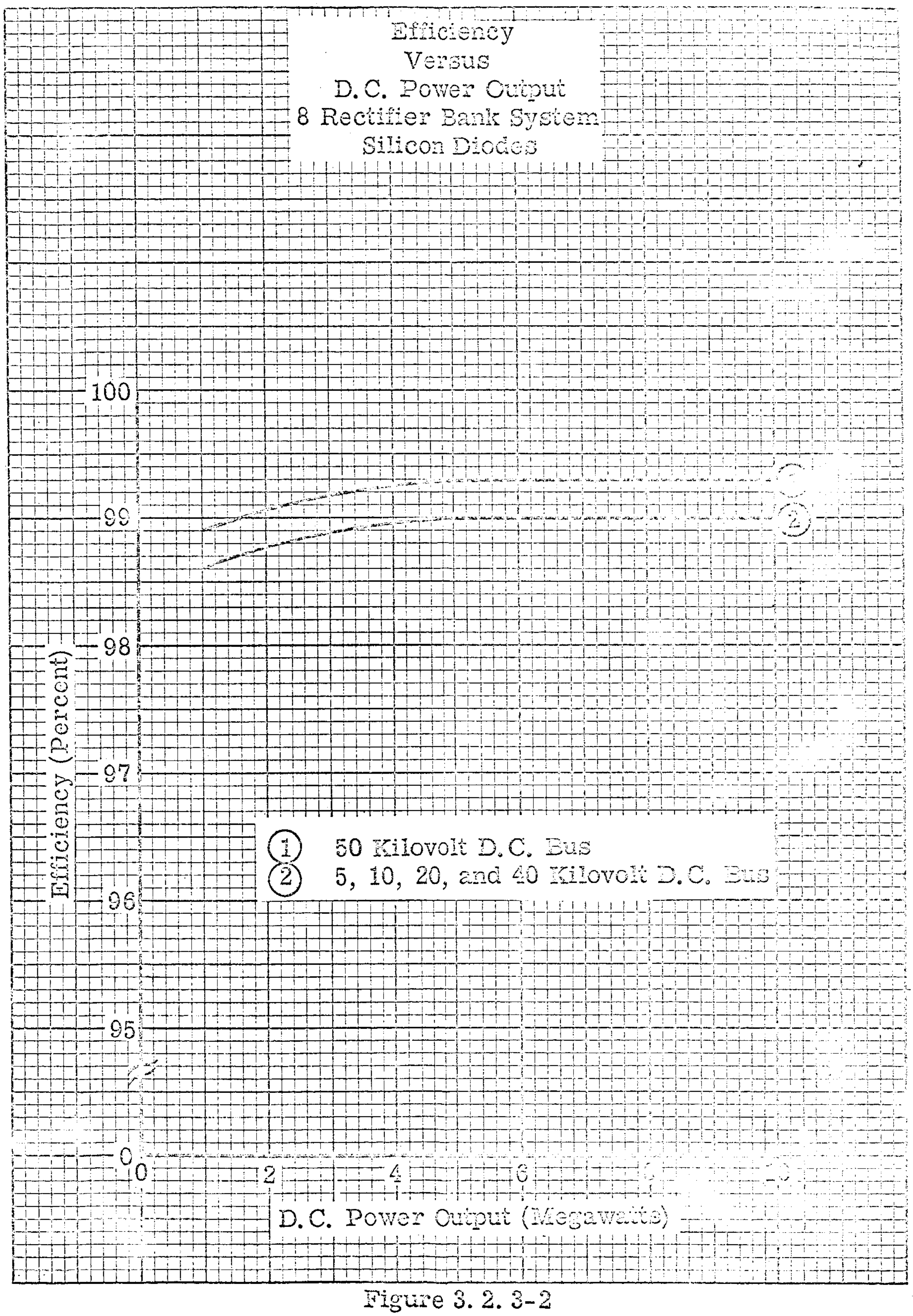

Efficiency
Versus
D.C. Bus Voltage
8 Rectifier Bank
1, 5, and 10 Megawatt System
Silicon Diodes
100
99
98
97
96
95
0
Efficiency (Percent)
0
10
20
30
D.C. Bus Voltage (Kilovolts)
① 5 and 10 Megawatt System,
Diodes Similar to JEDEC 1N3170
② 1 Megawatt System,
Diodes Similar to JEDEC 1N1190

Figure 3. 2. 3-1



Efficiency
Versus
D. C. Power Output
8 Rectifier Bank System
Silicon Diodes
100
99
98
97
96
95
0
Efficiency (Percent)
1 50 Kilovolt D. C. Bus
2 5, 10, 20, and 40 Kilovolt D. C. Bus
0
2
4
6
D. C. Power Output (Megawatts)

Figure 3. 2. 3-2

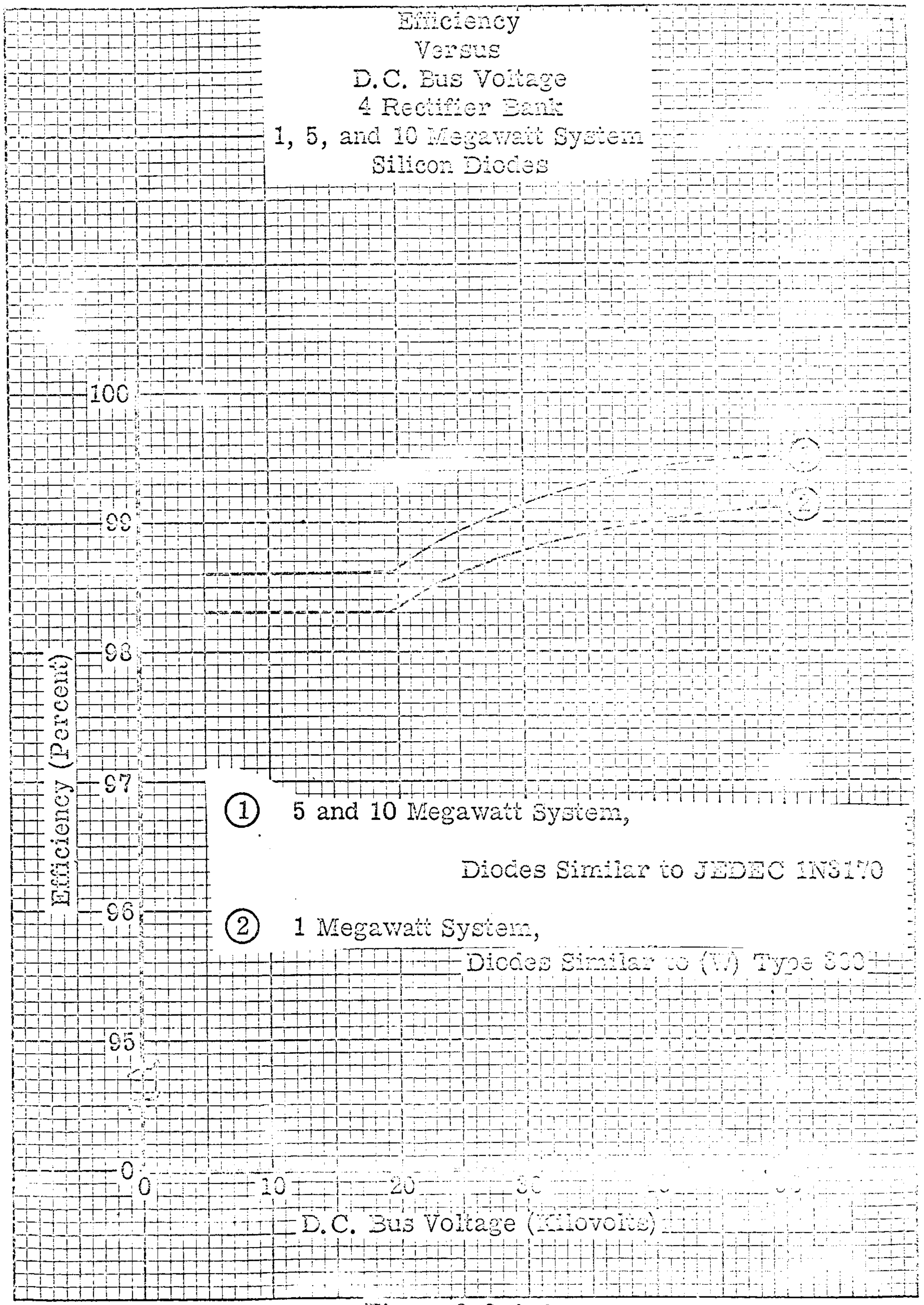

Efficiency
Versus
D.C. Bus Voltage
4 Rectifier Bank
1, 5, and 10 Megawatt System
Silicon Diodes
Efficiency (Percent)
100
99
98
97
96
95
0
0
10
20
30
D.C. Bus Voltage (Kilovolts)
1 5 and 10 Megawatt System,
Diodes Similar to JEDEC 1N3170
2 1 Megawatt System,
Diodes Similar to (W) Type 300

Figure 3. 2. 3-3

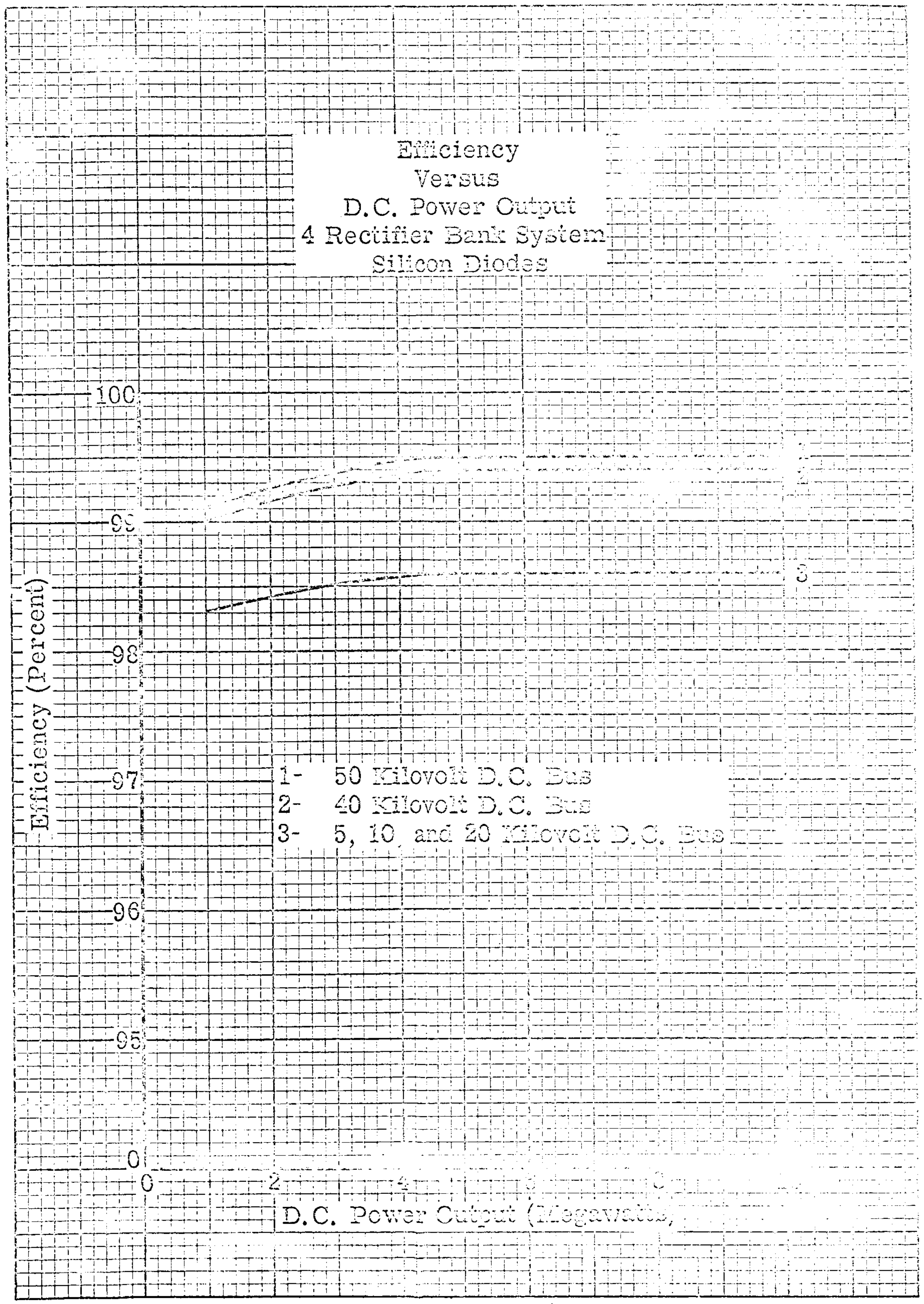

Efficiency
Versus
D.C. Power Output
4 Rectifier Bank System
Silicon Diodes
100
99
98
97
96
95
0
Efficiency (Percent)
3
1- 50 Kilovolt D.C. Bus
2- 40 Kilovolt D.C. Bus
3- 5, 10 and 20 Kilovolt D.C. Bus
0
2
4
6
8
D.C. Power Output (Megawatts)

Figure 3. 2. 3-4

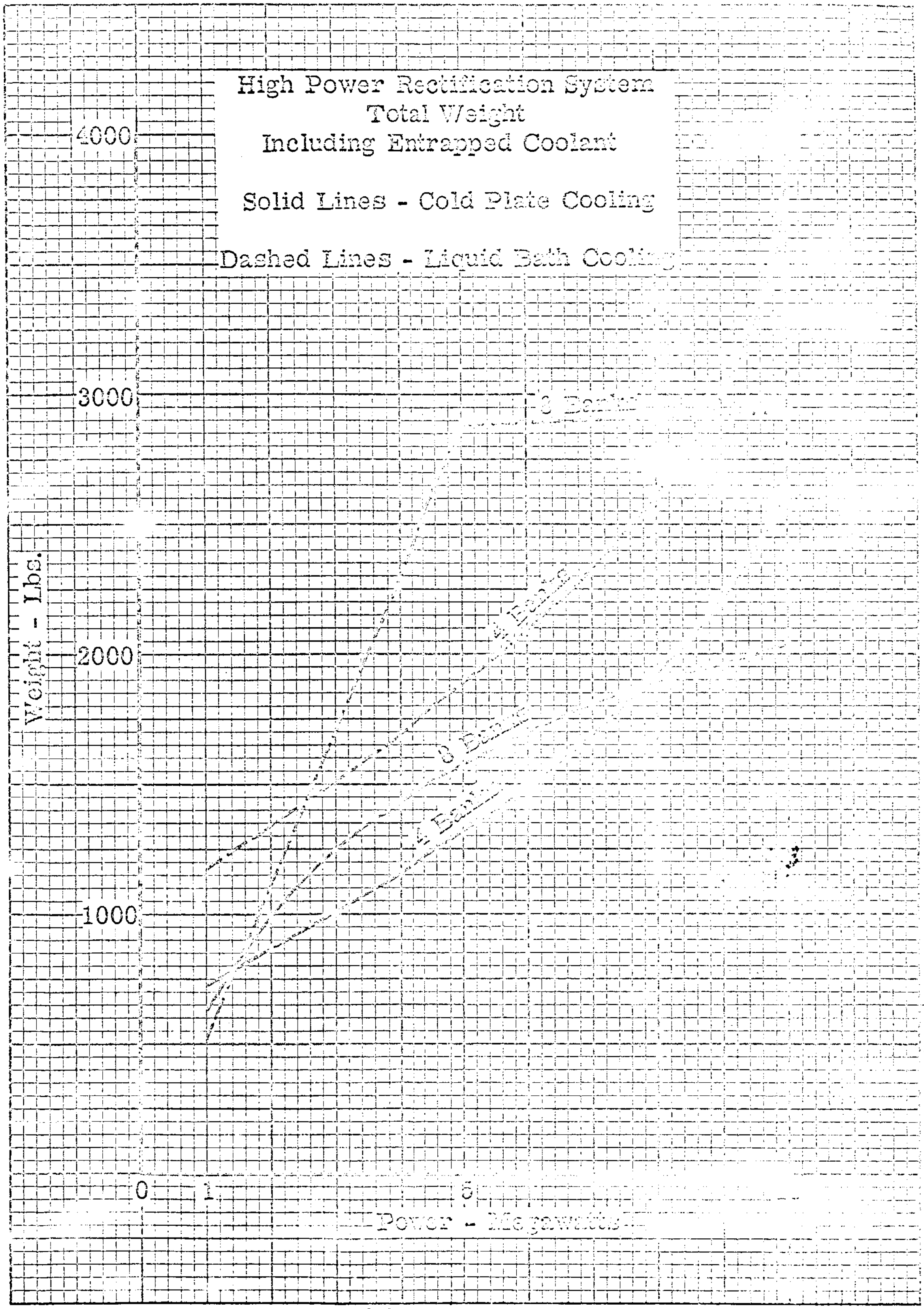
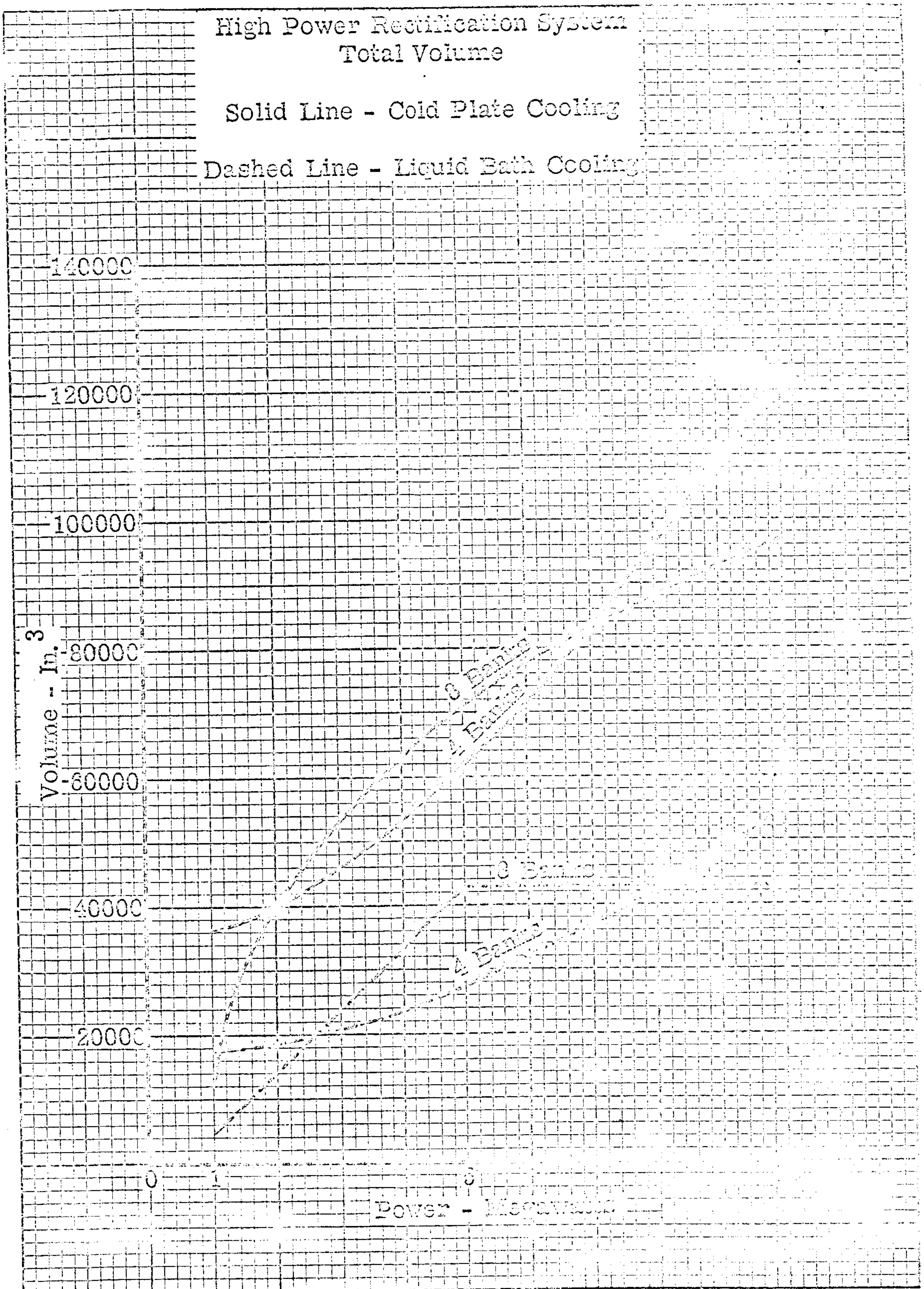
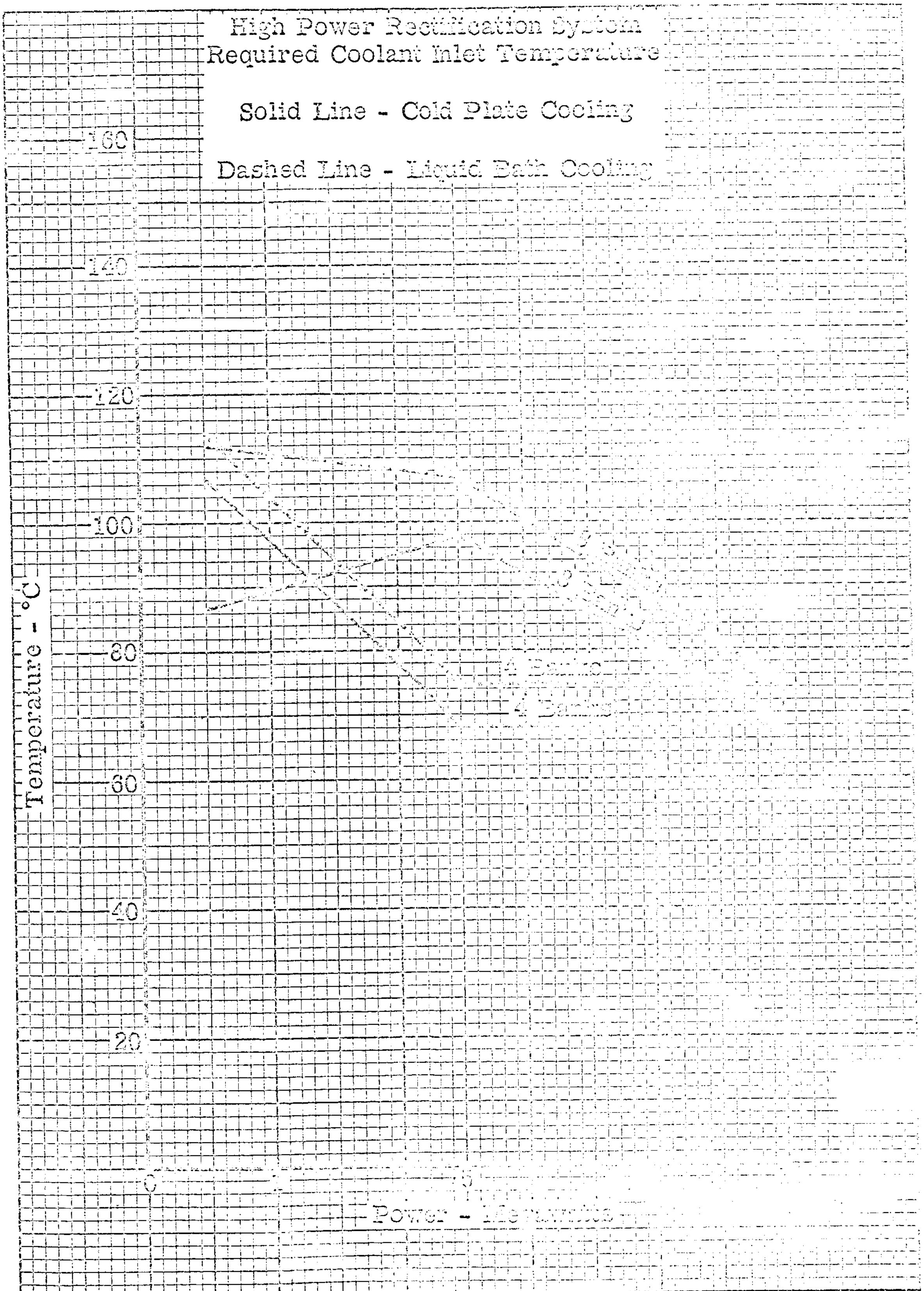

High Power Rectification System
Total Weight
Including Entrapped Coolant
Solid Lines - Cold Plate Cooling
Dashed Lines - Liquid Bath Cooling
4000
3000
2000
1000
Weight - Lbs.
0
1
5
Power - Megawatts
4 Banks
3 Banks
4 Banks

Figure 3. 2. 3-5



High Power Rectification System
Total Volume
Solid Line - Cold Plate Cooling
Dashed Line - Liquid Bath Cooling
140000
120000
100000
80000
60000
40000
20000
Volume - In.3
6 Banks
4 Banks
6 Banks
4 Banks
0
1
5
Power - Megawatts

Figure 3. 2. 3-6



High Power Rectification System
Required Coolant Inlet Temperature
Solid Line - Cold Plate Cooling
Dashed Line - Liquid Bath Cooling
160
140
120
100
80
60
40
20
Temperature - °C
4 Banks
0
5
Power

Figure 3. 2. 3-7

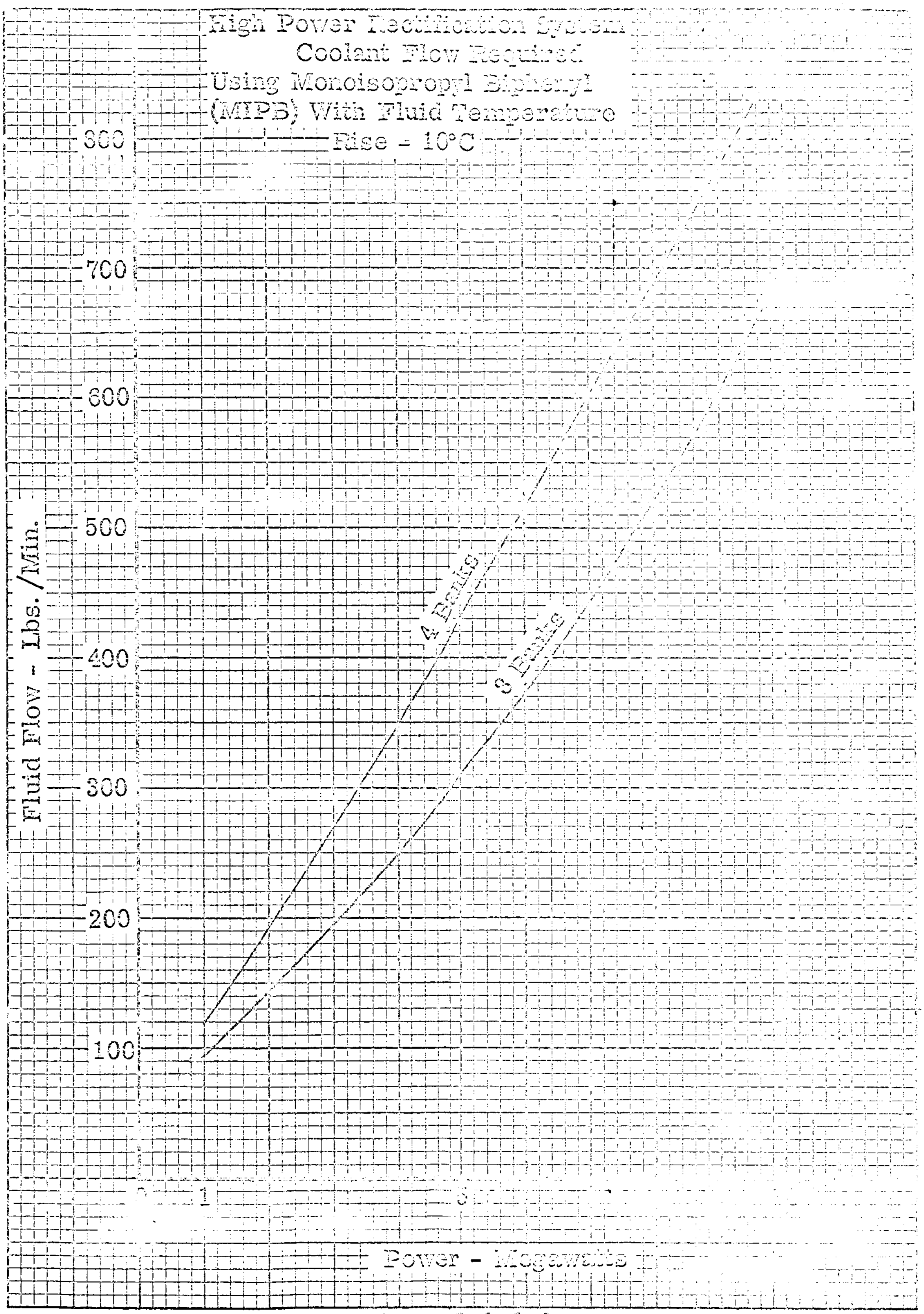

High Power Rectification System
Coolant Flow Required
Using Monoisopropyl Biphenyl
(MIPB) With Fluid Temperature
Rise = 10°C
Fluid Flow - Lbs./Min.
800
700
600
500
400
300
200
100
4 Banks
3 Banks
1
3
Power - Megawatts

Figure 3. 2. 3-3

The rectifier-system total weight is shown in Figure 3. 2. 3-5. In all cases, this includes the weight of coolant fluid entrapped within the system. Total volume is shown in Figure 3. 2. 3-6. For the liquid-bath-cooled, 8-bank system it will be noted that the volume is the same for the 5 and 10-megawatt power ratings, and that the weight is nearly identical. The only difference, in fact, lies in a slightly increased electrical interconnecting conductor weight at 10 megawatts. The reason for this is that with liquid bath cooling, the determining factor in size and weight is the volume and structure required to package the 1056 diodes similar to Type JEDEC IN3170 used in both cases. The difference in the heat load of these diodes between the 5 and 10 megawatt cases is reflected in the coolant flow and inlet temperature requirements.

Figure 3. 2. 3-7 presents required coolant inlet temperature, drawn as straight-line segment curves. For cold-plate cooling, the required coolant inlet temperature is determined as:

$$T_{f_i} = T_{conduit} - \Delta T_{convection} - \Delta T_{fluid}$$

Where $T_{conduit}$ = Allowable cold-plate conduit internal wall temperature, found from modified curves similar to quarterly report Figure 3. 2. 4. 7.

$\Delta T_{convection}$ = Temperature rise through the convection film layer, assumed to be 10°C.

ΔT_{fluid} = Temperature rise of coolant fluid due to heat absorption, assumed to be 10°C.

For liquid-bath cooling, the coolant inlet temperature is:

$$T_{f_i} = T_{junction} - \Delta T_{junction\ \ stud} - \Delta T_{convection} - \Delta T_{fluid}$$

where $\Delta T_{junction \rightarrow stud}$ is the junction to stud temperature drop determined from thermal resistance as specified by the supplier. The diode stud temperature and case temperature are assumed to be identical. The fluid temperature rise is again assumed to be 10°C. Both cooling method analyses assume a junction temperature of 142°C derated 25% from the supplier's specified maximum of 190°C.

With both cooling systems the required coolant temperature to maintain the 142°C junction desired is a function of the rectifier type and the heat to be dissipated from each rectifier. Therefore, the temperature required by the 4 bank system is the same at both 5 and 10 megawatts, since both use the same diode dissipating 97 watts each. The difference in overall heat loss, as a result of different quantities of diodes, is reflected in the required coolant flow, shown in Figure 3.2.3-8.

It is interesting to note that for the 8-bank,cold-plate system, the required coolant inlet temperature is lower for the 1-megawatt rating system than for the 5 megawatt. This results from the use of a smaller diode, similar to Type JEDEC IN1190, with a comparatively high thermal resistance and low surface area for the 1 megawatt system.

Required coolant flow is assumed to be a function of heat load and temperature rise and is therefore assumed to be the same for both cold-plate and liquid-bath methods of cooling. Figure 3.2.3-8 is based on an allowed coolant temperature rise of 10°C. The data was obtained from Quarterly Report Number 1, Figure 3.2.4-2.

3.2.3.3 High-Temperature, Semiconductor-Diode Rectifier-Circuit Parametric Data

The present and estimated advances in the state-of-the-art of high temperature semiconductor diodes, such as gallium arsenide and silicon carbide, as determined from the First Quarterly Report, is inadequate to provide high-power, high-voltage rectification. The application of these devices to this space application is, therefore, premature and will be deferred.

3.2.3.4 High-Temperature Gas-Tube-Diode Rectifier-Circuit Parametric Data

Electrical System

The Wye, 6-Phase, Delta, Double-Way (Bridge) Circuit has been retained for the hydrogen-gas-tube-diode rectification parametric study. The transformer parametric study presented as a separate write-up will include the transformer requirements for gas tube filament power. The gas-tube filament power losses are included and appear under diode losses in the prepared tables. It should be re-emphasized at this point that the gas-tube diode considered in this study has not been developed. The performance characteristics of the tube is based on extrapolated data of an existing 10-ampere, 200 PIV design.

Tables 3.2.3-7 through 3.2.3-9 list the diode quantity, volume, weight, and power losses for an 8-bank gas-tube rectifier system capable of pro-

Diode

TABLE 3.2.3-7

10 Megawatt - 8 Rectifier Bank Gas Tube Diode System

D-C Bus Volts	5 KV	10 KV	20 KV	40 KV	50 KV
Rect. Bank Condition	96 Par. 1 Ser.	48 Par. 2 Ser.	24 Par. 4 Ser.	12 Par. 8 Ser.	12 Par. 8 Ser.
Load D-C Amps	2000	1000	500	250	200
Amps/3 Phase Bridge	20.8	20.8	20.8	20.8	16.7
Amps/Bridge Leg Peak Amps Avg. Amps	 20.8 6.95	 20.8 6.95	 20.8 6.95	 20.8 6.95	 16.7 5.57
Diode PIV	50 KV	50 KV	50 KV	50 KV	50 KV
Diodes/3 Phase Bridge	6	6	6	6	6
Total No. Diodes	576	576	576	576	576
Diode Type	G.E. Z 5437 Except 50 KV PIV	G.E. Z 5437 Except 50 KV PIV	G.E. Z 5437 Except 50 KV PIV	G.E. Z 5437 Except 50 KV PIV	G.E. Z 5437 Except 50 KV PIV
*Watts Loss/Diode	303.5	303.5	303.5	303.5	262
Total Diode Loss	174,816	174,816	174,816	174,816	150,812
PIV, Multip. Factor	9.52	4.76 9.52	4.76 9.52	4.76 9.52	7.62
Total Diode Wt. (#)	1510	1510	1510	1510	1510
Total Diode Vol. (IN^3)	34,400	34,400	34,400	34,400	34,400
Total Watts Loss	174,816	174,816	174,816	174,816	150,812

* Includes Filament Power

Diode

TABLE 3. 2. 3-8

5 Megawatt - 8 Rectifier Bank Gas Tube Diode System

D-C Bus Volts	5 KV	10 KV	20 KV	40 KV	50 KV
Rect. Bank Condition	48 Par. 1 Ser.	24 Par. 2 Ser.	12 Par. 4 Ser.	6 Par. 8 Ser.	6 Par. 8 Ser.
Load D-C Amps	1000	500	250	125	100
Amps/3 Phase Bridge	20.8	20.8	20.8	20.8	16.7
Amps/Bridge Leg Peak Amps Avg. Amps	 20.8 6.95	 20.8 6.95	 20.8 6.95	 20.8 6.95	 16.7 5.57
Diode PIV	50 KV	50 KV	50 KV	50 KV	50 KV
Diodes/3 Phase Bridge	6	6	6	6	6
Total No. Diodes	288	288	288	288	288
Diode Type	G.E. Z 5437 Except 50 KV PIV	G.E. Z 5437 Except 50 KV PIV	G.E. Z 5437 Except 50 KV PIV	G.E. Z 5437 Except 50 KV PIV	G.E. Z 5437 Except 50 KV PIV
*Watts Loss/Diode	303.5	303.5	303.5	303.5	262
Total Diode Loss	87,408	87,408	87,408	87,408	75,456
PIV, Multip. Factor	9.52	4.76 9.52	4.76 9.52	4.76 9.52	7.62
Total Diode Wt. (#)	755	755	755	755	755
Total Diode Vol. (IN^3)	17,200	17,200	17,200	17,200	17,200
Total Watts Loss	87,408	87,408	87,408	87,408	75,456

*Includes Filament Power

Diode

TABLE 3. 2. 3-9

1 Megawatt - 8 Rectifier Bank Gas Tube Diode System

D-C Bus Volts	5 KV	10 KV	20 KV	40 KV	50 KV
Rectifier Bank Condition	8 Par. 1 Ser.	4 Par. 2 Ser.	2 Par. 4 Ser.	8 Ser.	8 Ser.
Load D-C Amps	200	100	50	25	20
Amps/3 Phase Bridge	25	25	25	25	20
Amps/Bridge Leg Peak Amps Avg. Amps	 25 8.33	 25 8.33	 25 8.33	 25 8.33	 20 6.67
Diode PIV	50 KV	50 KV	50 KV	50 KV	50 KV
Diodes/3 Phase Bridge	6	6	6	6	6
Total No. Diodes	48	48	48	48	48
Diode Type	G.E. Z 5437 Except 50 KV PIV	G.E. Z 5437 Except 50 KV PIV	G.E. Z 5437 Except 50 KV PIV	G.E. Z 5437 Except 50 KV PIV	G.E. Z 5437 Except 50 KV PIV
*Watts Loss/Diode	345	345	345	345	295
Total Diode Loss	16,560	16,560	16,560	16,560	14,160
PIV, Multip. Factor	9.52	4.76 9.52	4.76 9.52	4.76 9.52	7.63
Total Diode Wt. (#)	126	126	126	126	126
Total Diode Vol. (IN^3)	2860	2860	2860	2860	2860
Total Watts Loss	16,560	16,560	16,560	16,560	14,160

*Includes Filament Power

viding 1, 5, and 10 megawatts at system direct current voltages of 5, 10, 20, 40, and 50 kilovolts. Because of the low current capability of the individual gas-tube diodes, six permanently paralleled bridges are required for the 5-megawatt system and 12 for the 10-megawatt system. The proposed arrangement is desirable electrically, but will be cumbersome from a mechanical standpoint. Diodes in series are not necessary because a 50 KV PIV rating can be provided in a single gas-tube diode. As a minimum value, therefore, the PIV multiplying factor is approximately twice the value of the silicon-rectifier system.

The 4-bank system was rejected as impractical because it required twice the number of fixed parallel bridges.

Comparison of rectifier efficiency to the direct-current system power and voltage requirements is shown in Figures 3.2.3-9 and 10.

Cooling System

Curves are presented showing the variation of total weight and volume, required coolant flow, and required coolant inlet temperature for 8-bank gas-tube rectifier systems of 1, 5, and 10 megawatts. A radiation cold-plate cooling system and a liquid bath cooling system are considered using Monsanto Chemical Company OS-124 coolant. Coolant flow and inlet temperature curves are based on an assumed coolant temperature rise of 10°C in the system, to facilitate comparison with the silicon-rectifier system.

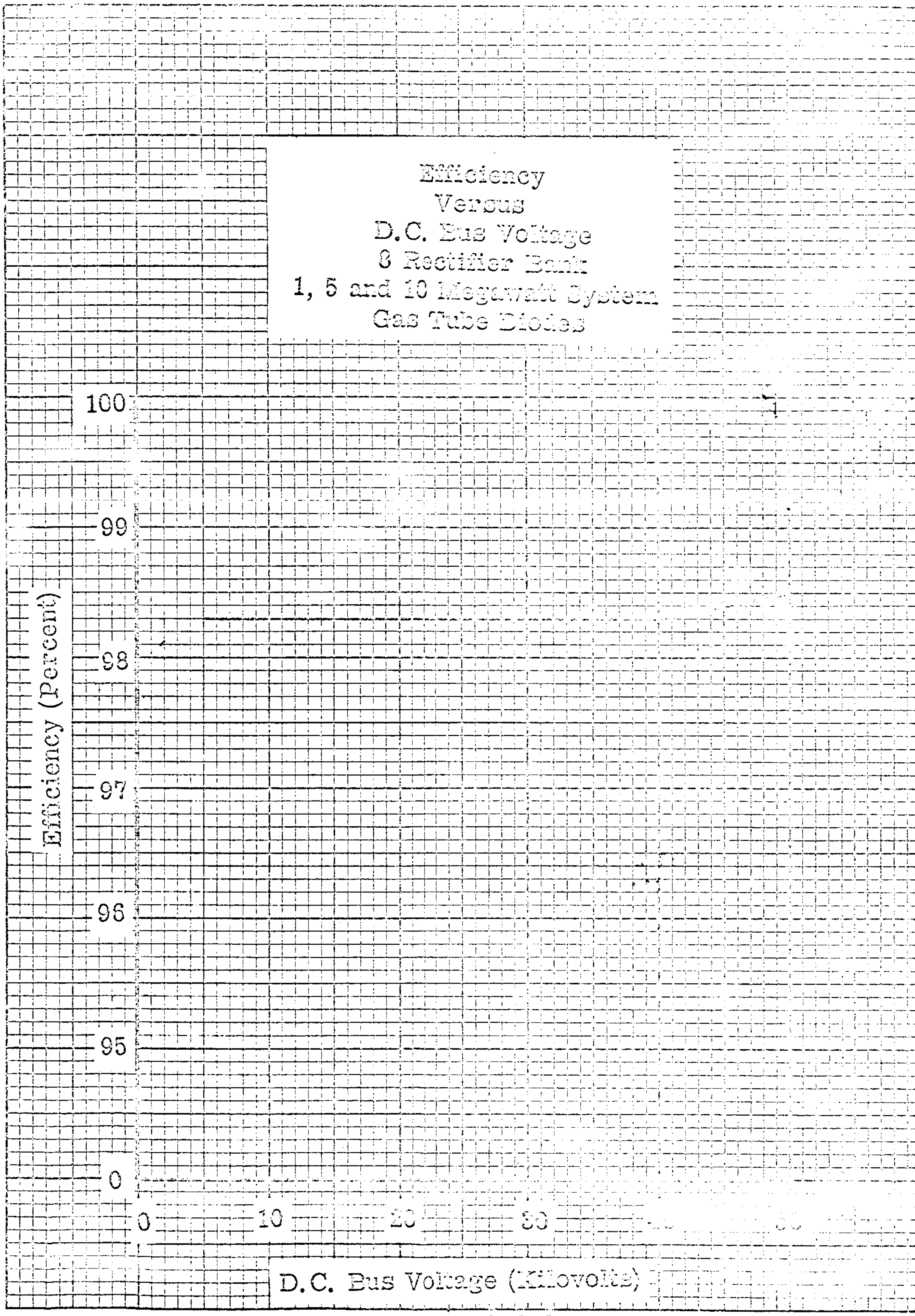

Efficiency
Versus
D.C. Bus Voltage
8 Rectifier Bank
1, 5 and 10 Megawatt System
Gas Tube Diodes
100
99
98
97
96
95
0
Efficiency (Percent)
0
10
20
30
D.C. Bus Voltage (Kilovolts)

Figure 3. 2. 3-9

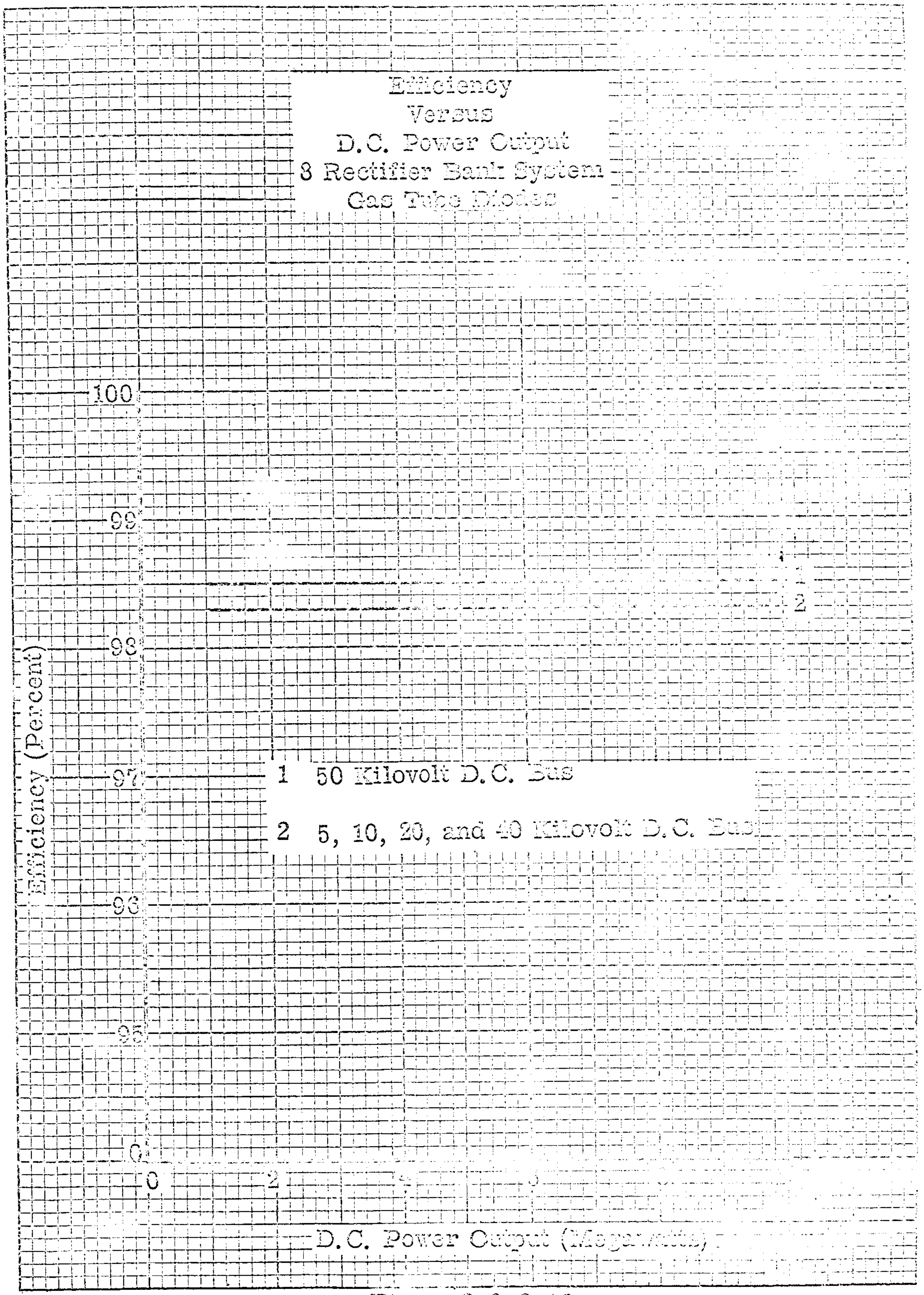


Figure 3.2.3-10

In the radiation cold-plate cooling system, the gas-tube diodes are assumed to be mounted between cold-plate walls. Beryllium oxide sheet is assumed as insulation to reduce the spacing between the cold-plate surface and the gas-tube diodes. The diodes are assumed to radiate heat to the walls, which in turn transfer the heat by convection to the contained coolant fluid. Cooling tube design requirements are based on an assumed convection film coefficient of 0.500 watts/IN^2 -°C. In the liquid-bath cooling system, coolant fluid is passed directly over the gas tubes rather than through a separate cold plate. Beryllium oxide barriers are used between tubes to duct coolant fluid while maintaining dielectric strength. With OS-124 coolant fluid, in this application, the surface convection film coefficient is assumed to be 0.125 watts/ IN^2 - °C.

The rectification system total weight is shown in Figure 3.2.3-11 and total volume in Figure 3.2.3-12. The weight includes entrapped coolant for both cooling methods. Unlike silicon-rectifier systems, the weight and volume of gas-tube-rectifier systems is substantially lower when the liquid-bath cooling method is employed. This is due primarily to the ability of gas-tube rectifiers to make more efficient use of packaging volume, thus requiring a lower percentage of entrapped coolant than the silicon-rectification system. In this application the weight of additional entrapped coolant in the liquid bath is considerably less than the weight of required cold-plate structure with the cold-plate cooling. It is felt that the weight and volume differential between the two cooling methods can be reduced by design,

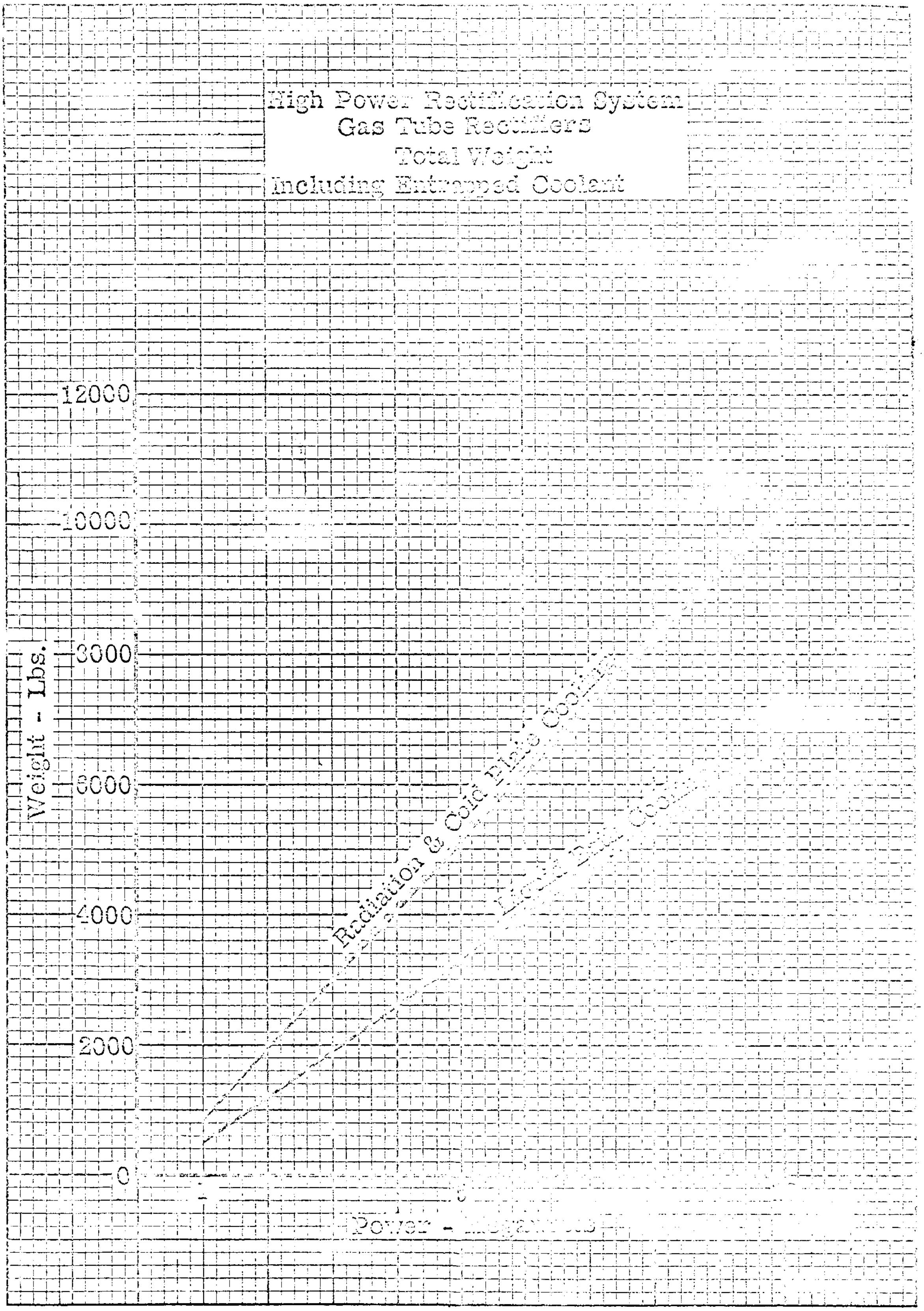


Figure 3. 2. 3-11

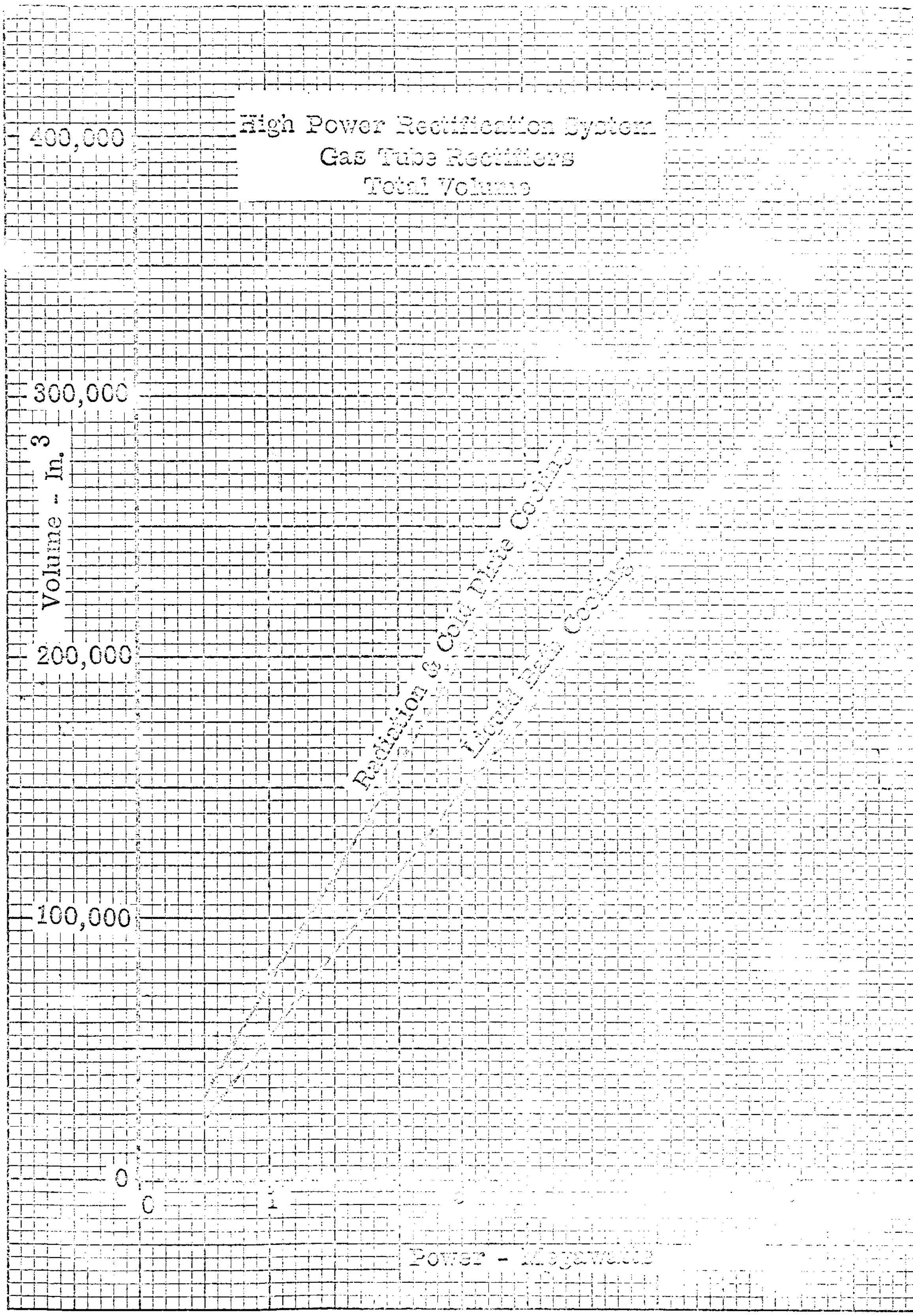


Figure 3. 2. 3-12

however, the trend should remain the same. Figure 3.2.3-13 shows maximum allowable coolant inlet temperature, based on an assumed maximum gas-tube rectifier surface temperature of 150°C. The maximum allowable coolant temperature is slightly lower in the one-megawatt system than in the five and ten megawatt systems, because the heat load per tube is slightly higher for this system. The maximum allowed temperature with the radiation, cold-plate method is considerably lower than that with the liquid bath, due to the large temperature drop in radiation between the gas-tube rectifier and the cold-plate walls.

Required coolant flow, see Figure 3.2.3-14, is assumed to be strictly a function of heat load and temperature rise and is therefore the same for both methods of cooling. The data presented are based on an allowed coolant temperature rise of 10°C, and are obtained from Quarterly Report Number 1, Figure 3.2.4-3.

3.2.3.5 Summary

The rectifier efficiency of the silicon-diode systems is higher than the gas-tube diode system over the considered direct-current, output-voltage range of 5 to 50 kilovolts and 1 to 10 megawatts.

Because the weight of the gas-tube-diode system, shown in Figure 3.2.3-11, does not include the weight of the filament transformers, the total weight of the silicon-diode system is less than the gas-tube-diode system for all three

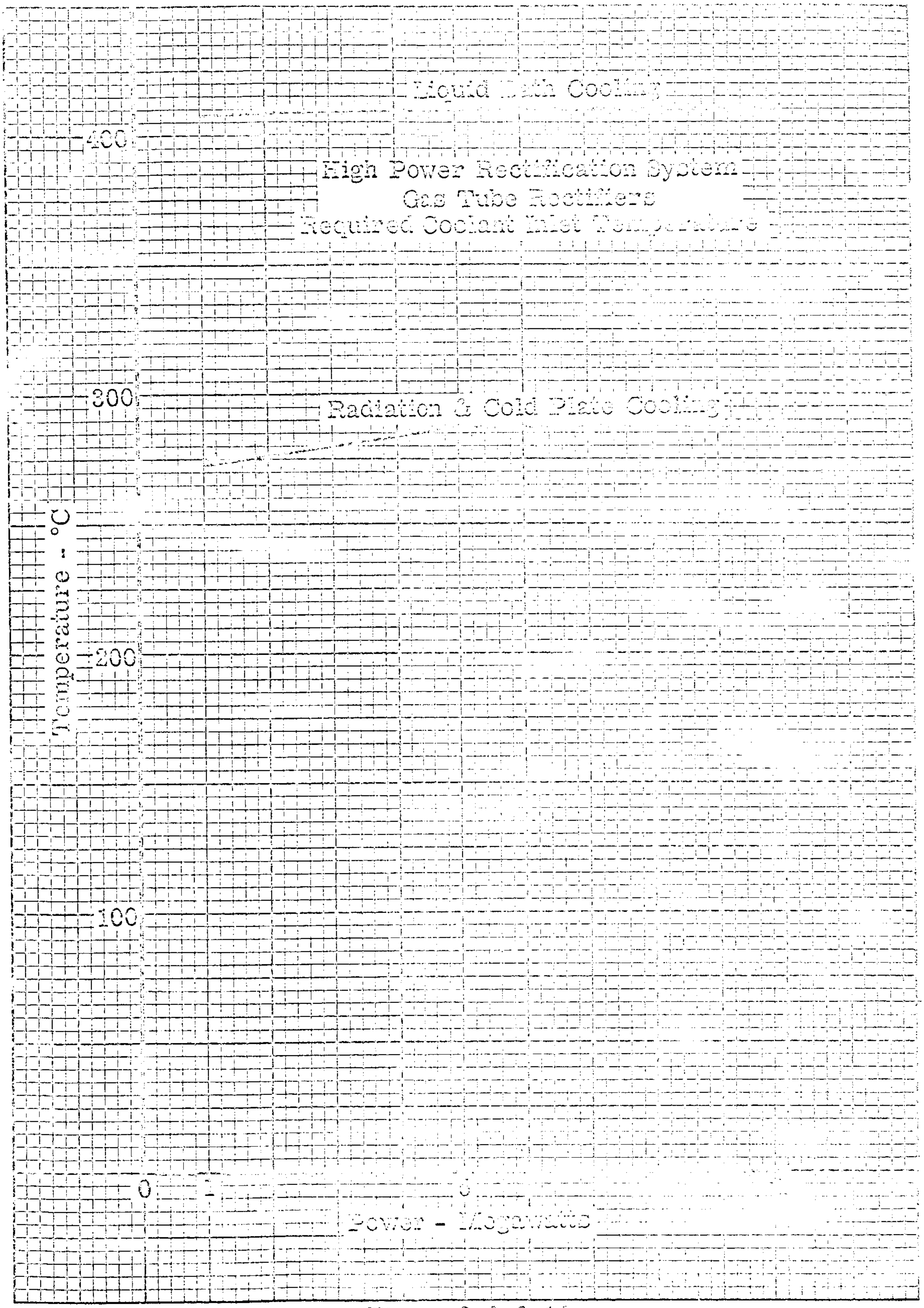


Figure 3. 2. 3-13

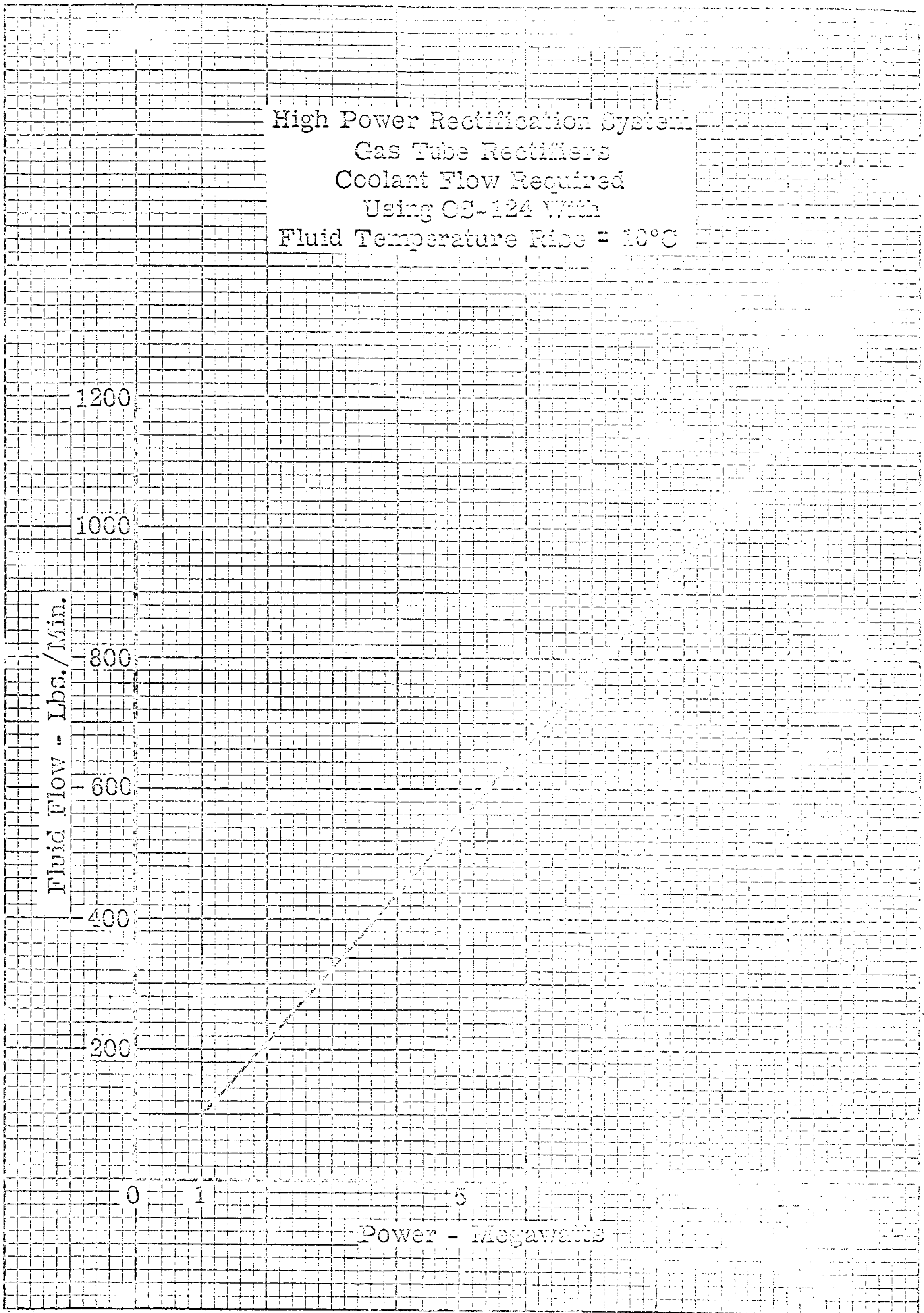


Figure 3. 2. 3-14

power output conditions. Comparing the 8-rectifier-bank systems only, the silicon diodes also require less volume than the gas-tube diodes, for liquid-bath cooling. Of the two silicon-diode systems considered, the 4-rectifier-bank system is more efficient than the 8-bank system from 30 to 50 KV for power outputs of 1, 5, and 10 megawatts.

It appears that liquid-bath cooling yields the best weight, volume, and coolant temperature results for gas-tube rectifiers, while in the silicon rectifier system, cold-plate cooling shows the best weight and coolant temperature data. In comparison with the silicon-rectification system, the gas-tube rectifier system offers a higher allowable coolant temperature range in exchange for higher required weight, volume and coolant flow.

3.2.4 Transformer Parametric Data

Transformer designs were made for 10, 5, and 1 megawatts of power at maximum operating temperatures of 500°F, 1000°F, and 1500°F. These conditions were selected to provide the maximum of information to aid in determining a system and to show penalties incurred.

Most of the data is for a temperature of 500°F with enough data to show the general characteristics of parameters at the 1000°F and 1500°F conditions.

A number of important facts have been brought to light by the data produced. These facts are:

1. A large percentage change in transformer weight produces only a small percentage change in transformer losses.
2. Except for some limitations, the transformer electro-magnetic weight is practically independent of rating for equal conditions and efficiency.
3. Multiple output windings, to provide variable output voltages at constant output power, impose a weight penalty on the transformer.
4. High voltages impose a weight penalty that increases in percentage as the size of the unit is reduced.
5. For the maximum temperature condition, 1500°F, a severe weight and loss penalty is incurred because the cobalt-iron alloys, required at this temperature, have higher losses.
6. From a weight-loss consideration, aluminum conductors offer little advantage over copper conductors.

Figure 3.2.4-1; Curves A, B, and C show losses versus copper and iron weights for 10, 5, and 1-megawatt transformers respectively. These transformers were designed for voltage variations from 5 KV to 50 KV and included: multiple secondary windings; winding output voltage variation of two to one, by limited generator excitation and primary taps; and insulated for operation at 50 KV d-c. The transformer weights and losses are tabulated in Table 3.2.4-1 and -2, for both the minimum and maximum output voltages.

Figure 3.2.4-2 shows losses/input power versus transformer copper and iron weights. The weights and losses from 10, 5, and 1 megawatt transformer ratings were used in plotting this curve. The curve shows that the weight is a function of losses/input power, or efficiency for given operating conditions and not a function of the power rating. The limitations occur when the frequency or flux are at such a level that proper distribution of iron and copper losses are not possible, without the iron being saturated, or when additional insulation would be required because of voltage conditions. See Table 3.2.4-5.

Figure 3.2.4-1; Curves D and E, show losses versus weight of a transformer with a single winding capable of delivering 50 KV d-c and 5 KV d-c respectively. Curves A through E of figure 3.2.4-1 show the transformer weight penalties imposed by high-voltage and variable voltage at constant power requirements.

Figure 3.2.4-1; Curves F and G, show losses versus weight of a transformer for 1000°F and 1500°F respectively. The designs were made by attempting to hold the ratio of losses the same as the 500°F designs. A small weight-loss penalty is incurred on the 1000°F designs, because elevated temperatures

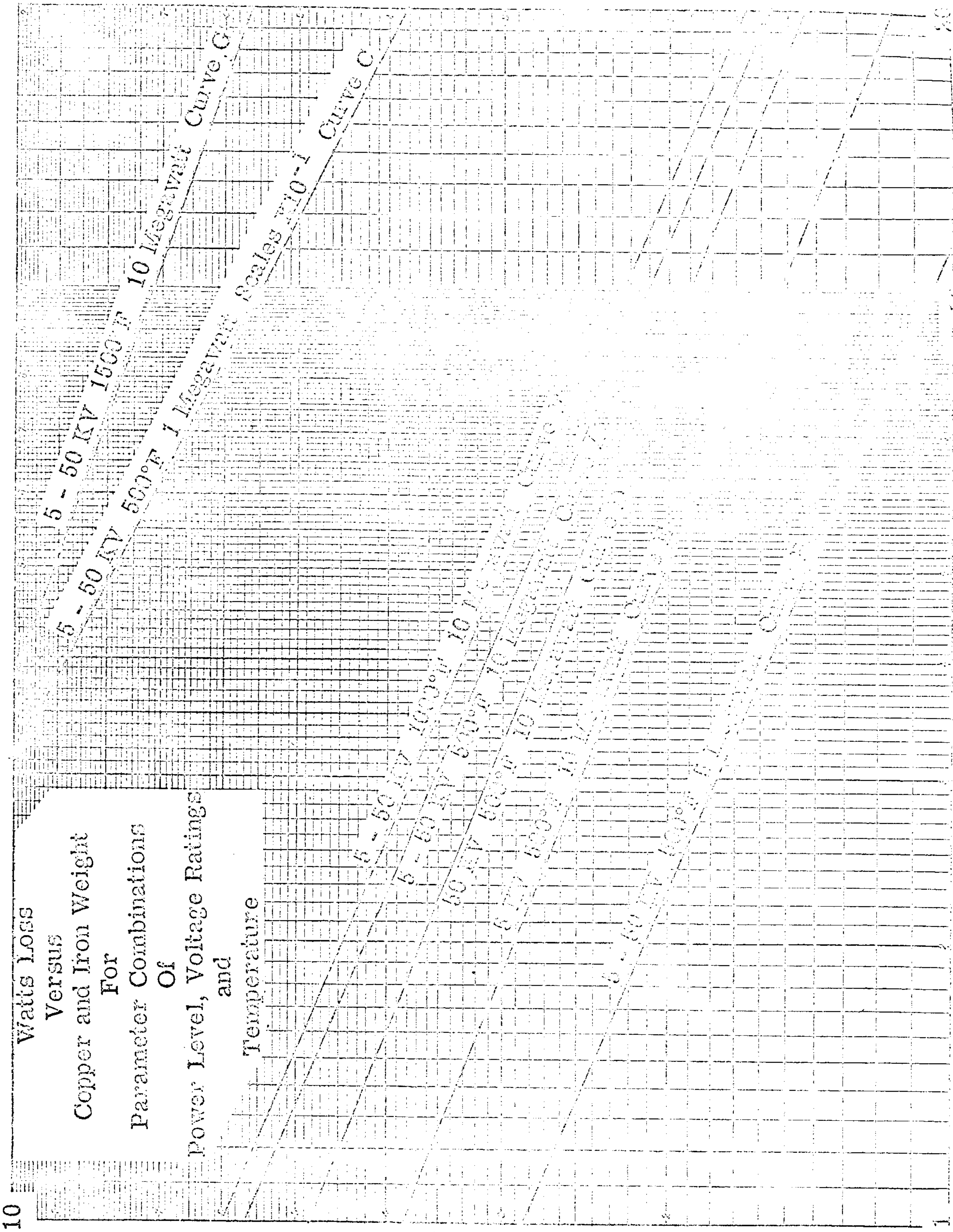
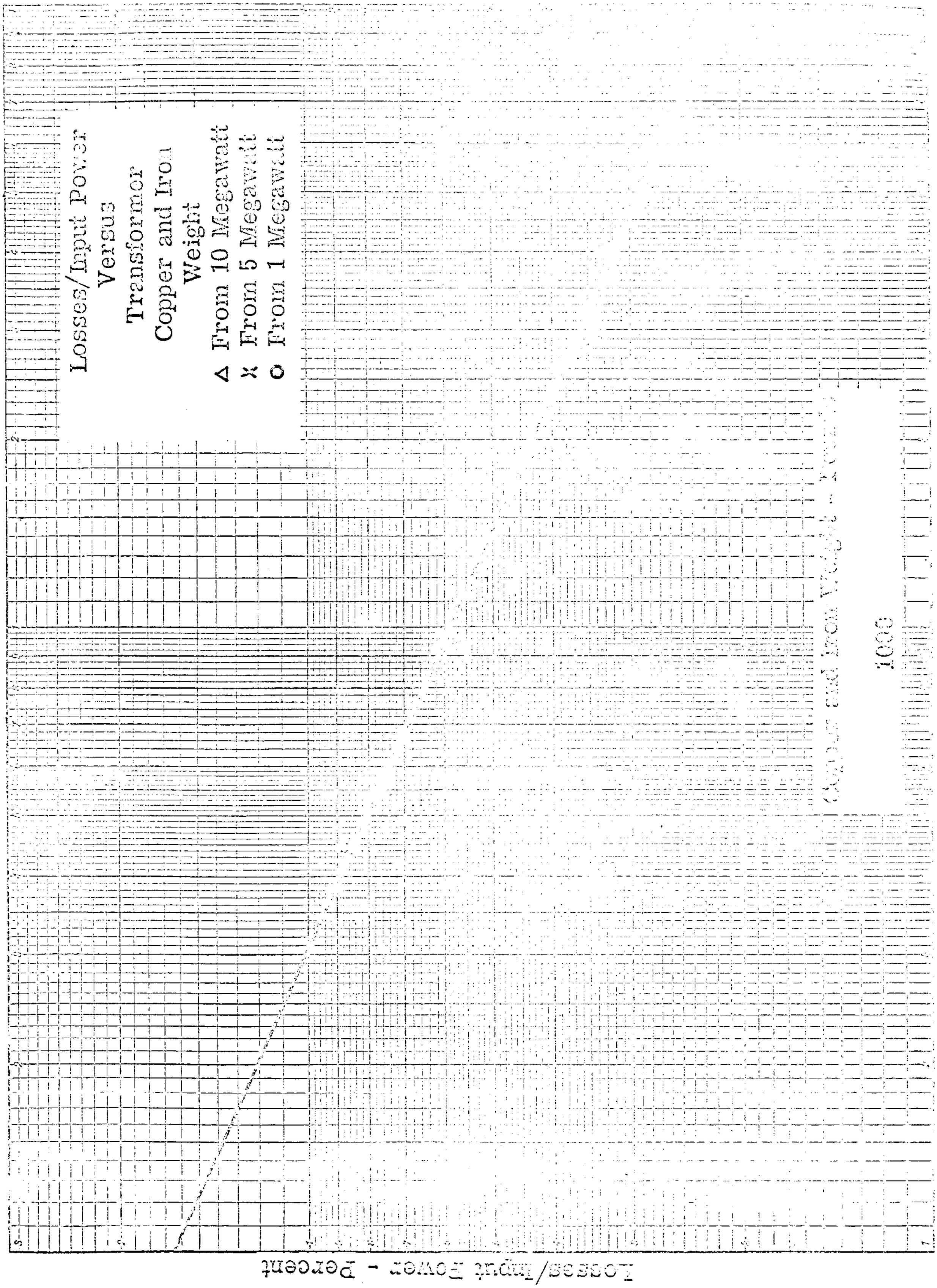

Watts Loss
Versus
Copper and Iron Weight
For
Parameter Combinations
Of
Power Level, Voltage Ratings
and
Temperature
5 - 50 KV 1500°F 10 Megawatt Curve C
5 - 50 KV 500°F 1 Megawatt Scales x10⁻¹ Curve C
Watts Loss x10⁻⁴
10
1
10

Figure 8. 2. 4-1



Losses/Input Power
Versus
Transformer
Copper and Iron
Weight
△ From 10 Megawatt
x From 5 Megawatt
o From 1 Megawatt
1000
Losses/Input Power - Percent

Figure 3.2.4-2

Table 3.2.4-1. Electro-Magnetic Weights and Losses

For 10-Megawatt, Multiple-Secondary Transformers

To Produce 5-50 KV d-c at Constant Power

Design Number	Copper Conductor			Aluminum Conductor		
	1	2	3	4	5	6
Conductor Weight	2,208	3,918	6,228	1,118	2,258	3.282
Iron Weight	1,870	2,630	3,530	1,983	3,050	4,100
Total Weight	4,078	6,548	9,758	3,101	5,308	7,382
I^2R Loss (1)	24,000	17,600	14,000	26,600	18,500	15,500
Iron Loss (1)	9,000	7,550	7,300	9,600	8,750	9,050
Total Loss (1)	33,000	25,150	21,300	36,200	27,250	24,550
I^2R Loss (2)	5,000	3,500	2,800	5,300	4,000	3,400
Iron Loss (2)	29,200	26,000	25,200	32,300	29,700	29,300
Total Loss (2)	34,200	29,500	28,000	37,600	34,500	32,700
Surface Area Square Inch	8,150	10,100	12,700	10,120	13,200	16,400
Watts Per Square Inch	4.05	2.49	1.68	3.6	2.07	1.5
Size	24 x 51 x 38	26 x 57 x 43	29 x 65 x 47	25 x 55 x 42	30 x 66 x 40	32 x 74 x 55

(1) Losses at 500°F for 5 KV d-c output per winding
(2) Losses at 500°F for 10 KV d-c output per winding

Table 3.2.4-2. Electro-Magnetic Weights and Losses

For Copper-Conductor, Multiple-Secondary Transformers

To Produce 5-50 KV d-c at Constant Power

Design Number	5 Megawatt			1 Megawatt		
	1	2	3	1	2	3
Conductor Weight	984	1,716	3,027	213	305	520
Iron Weight	850	1,215	2,000	234	231	405
Total Weight	1,834	2,931	5,027	447	536	935
I^2R Loss (1)	16,000	11,100	8,400	6,500	5,550	3,700
Iron Loss (1)	6,000	5,850	5,700	2,200	2,010	1,300
Total Loss (1)	22,000	16,950	14,100	8,700	7,560	5,000
I^2R Loss (2)	3,100	2,250	1,670	1,320	1,140	740
Iron Loss (2)	20,400	19,750	19,500	8,000	5,860	4,300
Total Loss (2)	23,500	22,000	21,170	9,320	7,000	5,040
Surface Area Square Inch	5,400	7,000	9,600	2,700	3,010	3,300
Watts Per Square Inch	4.07	2.42	1.47	3.17	2.51	1.51
Size	20 x 42 x 30	22 x 43 x 35	23 x 63 x 41	14 x 30 x 22	14 x 32 x 23	15 x 36 x 20

(1) Losses at 500°F for 5 KV d-c output per winding
(2) Losses at 500°F for 10 KV d-c output per winding

Table 3. 2. 4-3. Electro-Magnetic Weights and Losses

For 10-Megawatt, Multiple-Secondary Transformers

To Produce 5-50 KV d-c at Constant Power

Design Number	1000°F			1500°F		
	1	2	3	1	2	3
Conductor Weight	2,313	4,020	6,680	3,088	5,214	9,000
Iron Weight	1,680	2,370	3,530	1,205	1,875	3,220
Total Weight	3,993	6,390	10,190	4,293	7,000	12,220
I^2R Loss (1)	24,300	17,600	13,900	71,500	55,300	44,500
Iron Loss (1)	9,400	9,000	8,500	23,500	23,200	22,200
Total Loss (1)	33,700	26,600	22,400	94,000	78,500	66,700
I^2R Loss (2)	7,740	5,620	1,740	12,500	11,100	9,050
Iron Loss (2)	29,600	28,600	26,500	62,500	63,300	59,500
Total Loss (2)	37,340	34,220	28,240	75,000	74,400	68,550
Surface Area Square Inch	8,150	10,100	12,700	6,800	11,000	14,400
Watts Per Square Inch	4.14	2.63	1.76	11.05	7.13	4.64
Size	24 x 51 x 38	26 x 57 x 42	29 x 65 x 47	23 x 54 x 40	26 x 61 x 46	30 x 70 x 51

(1) Losses at Indicated Temp. for 5 KV d-c Output Per Winding
(2) Losses at Indicated Temp. for 10 KV d-c Output Per Winding

Table 3. 2. 4-4. Electro-Magnetic Weights and Losses

For Single-Secondary Transformers

To Produce 50 or 5 KV d-c

Design Number	50 KV d-c 10 Megawatt			5 KV d-c		
	1	2	3	10 Meg.	5 Meg.	1 Meg.
Conductor Weight	1,674	2,706	4,000	2,739	1,200	238
Iron Weight	1,915	2,730	4,200	2,045	975	210
Total Weight	3,589	5,436	8,200	4,784	2,175	448
I^2R Loss (1)	15,100	11,550	9,000	10,550	8,000	2,700
Iron Loss (1)	13,700	13,150	11,500	9,850	6,000	2,050
Total Loss (1)	28,800	24,700	20,500	20,400	13,500	4,800
Surface Area Square Inch	7,280	9,000	11,700	5,700	3,800	1,300
Watts Per Square Inch	3.93	2.34	1.75	3.50	3.57	3.67
Size	24 x 47 x 35	26 x 54 x 39	28 x 61 x 45	22 x 42 x 30	17 x 36 x 25	11 x 20 x 14

(1) Losses at 500°F

Table 3.2.4-5. Effect of Constant Efficiency On Electro-Magnetic Weights and Losses

For 1 and 10-Megawatt Transformers

	5-50 KV d-c		5 KV d-c	
	1	10	1	10
Conductor Weight	528	535	233	195
Iron Weight	405	405	210	226
Total Weight	933	940	443	421
Conductor Loss	3,700	37,200	2,750	32,400
Iron Loss	1,950	15,800	2,050	14,700
Total Loss	5,650	53,000	4,800	47,100
$\frac{\text{Losses}}{\text{Input}}$	.00565	.00530	.0048	.00471

increase the copper losses faster than the iron losses decrease. In addition, the copper loss is the larger percentage of the total losses. The 1600°F designs incurred a larger weight or loss penalty because cobalt-iron alloy must be substituted for oriented silicon-iron material. Cobalt-iron alloys have higher loss (watts per pound) than silicon-iron alloys.

Table 3.2.4-1 shows the weight and losses for designs using aluminum for the conductor. The data indicates there is no weight-loss advantage using aluminum as the conductor. Aluminum has a density of about one-third, and a conductivity of about 1 percent that of copper with the combination producing an aluminum weight of one-half the copper for the same conductivity. Because the aluminum is larger in size, more winding space is required; thus increasing the core mean-turn and weight. The larger conductor size also increases the mean-turn of the aluminum, its weight, and its resistance. This condition then requires the conductor size and weight, and the core size and weight to be further increases in order to maintain the same losses. Besides having no weight advantage, the volume of the transformer with the aluminum conductor is larger than the one with the copper conductor.

To supply variable voltage at constant power the transformers were designed with tapped primary winding and multiple output windings. So that equal current division between windings or rectifier bridges operating in parallel might be realized, the output windings were designed to have nearly equal impedances. In addition to the above factors, the following considerations were used in the design of the transformers: (1) Secondary insulation is based on a maximum of 10 KV d-c between adjacent windings, and 50 KV d-c between windings and ground. (2) Some small weight savings may be realized by altering the insulation systems which would result in an increase in cost. (3) The total losses are somewhat higher when the output voltage of the winding is the highest. Because of the construction of the transformer, it is believed the iron loss would be more readily dissipated and this higher loss was not considered too great a problem.

Only electro-magnetic weights are shown in the curves: Structural weights will be proportional. Because insulation weight is a function of voltage rating, the ratio of insulation weight to total transformer weight increases as the transformer rating is decreased. Figure 3.2.4-3 shows weight versus input power. It may be used to estimate transformers for other ratings.

For the high temperature-gas tube diode, rectifier systems, more diodes must operate in parallel and to provide for nearly equal current division, more transformer output windings are required. The weight of the transformer increases as the number of output windings. Additional transformer weight is required to supply power to the diode filaments. The additional weight required for supplying filament power will not follow the curve characteristics because the windings must be insulated for high voltage. The method of insulating, connecting, and switching rectifier banks would be an important factor in the transformer weight. For the 10 megawatt systems 54,270 watts of heater power are required.

Tables 3.2.4-6 and 7 summarize the total transformer weight and weight analysis calculations of the transformer designs in Tables 3.2.4-1, 2, 3 and 4.

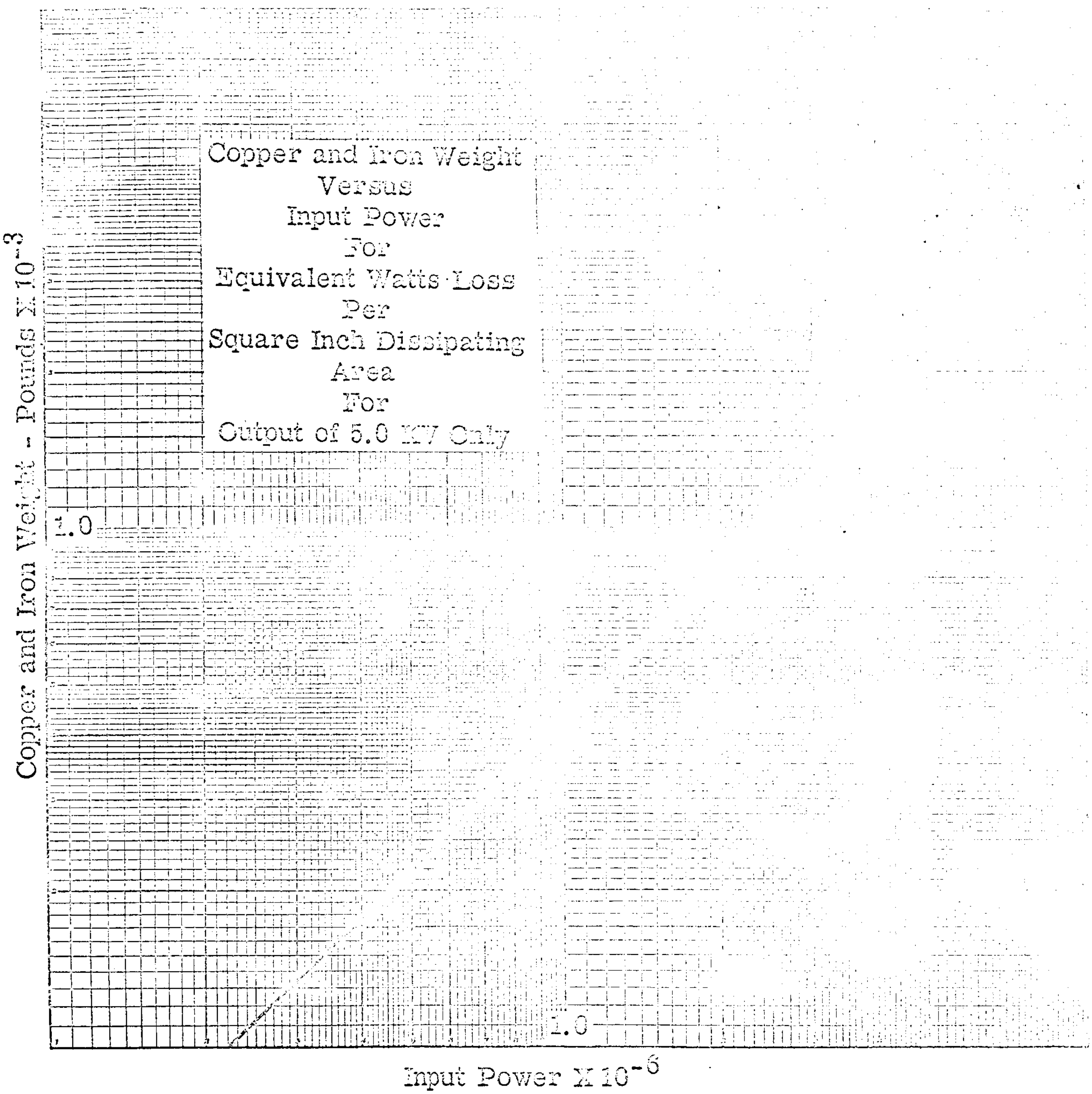

Copper and Iron Weight
Versus
Input Power
For
Equivalent Watts Loss
Per
Square Inch Dissipating
Area
For
Output of 5.0 KV Only
Copper and Iron Weight - Pounds X 10^{-3}
1.0
1.0
Input Power X 10^{-6}

Figure 3. 2. 4-3

Table 3.2.4-6. Effect of Coolant System on Transformer Weight
5-50 KV d-c, 500°F Temperature

		10 Megawatt			5 Megawatt			1 Megawatt		
1	Conductor Weight	2,208	3,918	6,228	984	1716	3027	213	284.4	528
2	Iron Weight	1,870	2,630	3,530	850	1215	2000	234	281	405
3	Electro-Magnetic Weight	4,078	6,548	9,758	1834	2931	5027	447	565.4	933
4	Percent Insulation	30	25	20	30	25	20	30	25	20
5	Percent Electro-Magnetic	70	75	80	70	75	80	70	75	80
6	Electro-Magnetic and Insul. Wt.	5,830	8,740	12,200	2320	3902	6290	639	754	1166
7	Total Trans. Weight *	7,290	10,920	15,200	3,275	4,880	7,850	799	941	1,458
8	Coolant System Dry Weight	105.5	91.0	80.4	72.5	67.9	65.3	28.8	24.35	17.43
9	Total Dry Weight	7,395.5	11,011.1	15,280.4	3347.5	4947.9	7915.3	827.8	965.35	1475.43
10	Coolant Flow Weight Lb/Min	100	100	100	100	100	100	100	100	100
11	Coolant System Wet Wt. Total	115.6	99.75	94.6	79.4	74.4	71.5	31.5	26.7	[illegible]
12	Total Wet Weight	7405.6	11,019.75	[illegible]	3354.4	4954.4	[illegible]	[illegible]	967.7	[illegible]
13	[illegible] Coolant Weight	10.1	8.75	8.2	6.9	6.5	6.2	2.7	2.35	1.67
14	[illegible]	1.56	.99	.005	2.30	1.5	.904	3.73	2.75	1.20

* [illegible]

Table 3.2.4-7. Effect of Coolant System on Transformer Weight

		5-50 KV d-c (10 Megawatts)						50 KV d-c (10 Megawatts)		
		Aluminum Conductor			1000°F					
1	Conductor Weight	1116	2253	3252	2313	4020	6636	1674	2706	4000
2	Iron Weight	1985	3050	4100	1680	2370	3530	1915	2730	4260
3	Electro-Magnetic Weight	3101	5303	7352	3993	6390	10,166	[illegible]	5436	8260
4	Percent Insulation	40	35	30	30	25	20	30	25	20
5	Percent Electro-Magnetic	60	65	70	70	75	80	70	75	80
6	Electro-Magnetic and Insul. Wt.	5170	8160	10,500	5700	8510	12,70[illegible]	5130	7250	10,320
7	Total Trans. Weight *	6400	10,200	13,110	7125	10,0[illegible]	15,8[illegible]	6410	9030	12,900
8	Coolant System Dry Weight	116.0	103.4	100.9	115.1	105.7	97.2	89.9	76.1	68.2
9	Total Dry Weight	6576	10,[illegible].4	13,210.9	7240.1	10,755.7	[illegible]	[illegible]	9106.1	12,[illegible]
10	[illegible] Weight	100	100	100	100	100	100	100	100	1[illegible]
11	[illegible] System [illegible] Total	127.0	116.6	110.5	123.1	115.6	95.5	97.4	83.5	[illegible]
12	[illegible] Weight	6567	10,316.6	13,220.5	7251.1	[illegible]	[illegible]	6507.4	[illegible]	[illegible]
13	[illegible] Coolant [illegible]	11.0	10.2	9.6	11.0	10.1	8.3	8.5	7.4	6.1
14	% [illegible] System	1.96	1.13	.83[illegible]	1.74	1.07	.593	1.400	.91	.535

* [illegible] no cooling [illegible] to support [illegible] wt. of 20% of total

Estimated percentage of insulation, etc. is shown on line 4. Total transformer packaged weight, not including cooling provisions, is shown on line 7. Cooling system dry weight is shown on line 8 with entrapped coolant weight shown on line 13. Total resultant packaged transformer weight, including entrapped coolant is shown on line 12.

Cooling system weights are based on the use of *OS-124 coolant for all 500°F systems, and eutectic Nak at 1000°F and 1500°F. To facilitate comparison of alternate designs, a coolant flow of 100 pounds per minute was assumed throughout the study.

Eutectic Nak was also considered for 500°F designs, because initial study indicated that the small convection film temperature drop of Nak might yield a lighter overall cooling system design. A more detailed investigation will be required to verify this initial indication.

In all cases, cooling was assumed to be accomplished by passing coolant through ducts over external surfaces of the core and coil. Ducts were assumed to be made of nickel or stainless steel to facilitate containment of eutectic Nak, and to be insulated from all windings.

Cooling system weight was found to be virtually proportional to transformer heat loss. The percentage of total weight comprised by the cooling system was found therefore to vary from about 0.5 percent to nearly 4 percent, depending on the magnitude of the losses in each individual case.

*Monsanto Chemical Co. Trade Mark

Cooling system design analysis for a coolant flow (W_f) of 100 pounds per minute is presented in Tables 3.2.4-8 and -9. Table 3.2.4-8 is for 10 megawatt and Table 3.2.4-9 is for 5 and 1-megawatt transformers. In each table, the sum of the temperature rises caused by fluid heat absorption, and convection film layer are listed in the column "Total Temperature Rise". Because the convection film co-efficient of eutectic Nak is exceptionally high, the temperature drop across the film will be in the order of 1 degree centigrade. See Quarterly Report Number 1, Figure 3.2.4-4.

In addition to the coolant flow of 100 pounds per minute, the following additional data was used in the analysis:

1. Average Temperature: 260°C for 500°F, 538°C for 1000°F and 815°C for 1500°F.
2. Coolant Characteristics

Coolant Characteristics	OS-124	Nak
Specific Heat	.50	.21
Film Coefficient	.5	20
Fluid Density	.0367	.0293

The tables show an overall coolant temperature rise for the transformer designs. There will also be a copper and iron temperature rise above the coolant temperature. This temperature rise is the gradient between surfaces in contact with the coolant and those that are not. The gradient is dependent upon the distance the heat has to travel and the insulation material type and thickness. If ducts were placed between coils and core, a 65 percent reduction in temperature gradient could be realized. Without ducts to cool the primary, the estimated temperature gradient would be in the range of

Table 3. 2. 4-8. Cooling System Weight and Temperature for Various Transformer Designs

Conductor & Iron Type	5 KV Total Losses Watts Qt.	10KV Total Losses Watts Qt.	Type Coolant	Coolant Fluid Temp. Rise	Convec-tion Temp. Rise	Total Temp. Rise °C	Tube Wt. Pounds	Fluid Wt. Pounds	Total Cooling Weight
Aluminum Silicon	30,200	37,000	OS-124	23	35	58	116.0	10.99	127.0
Aluminum Silicon	27,250	34,500	OS-124	22	32	54	106.4	10.03	116.6
Aluminum Silicon	24,550	32,700	OS-124	21	29	50	100.0	9.55	110.5
Copper Silicon	33,000	34,200	OS-124	22	31	53	105.5	10.12	115.62
Copper Silicon	33,000	34,200	NaK	52	1	53	81.7	6.25	87.95
Copper Silicon	25,150	29,500	OS-124	19	27	46	91	8.75	99.75
Copper Silicon	25,150	29,500	NaK	45	1	46	70.6	5.4	76.0
Copper Silicon	21,800	28,000	OS-124	18	26	44	83.4	8.16	91.6
Copper Silicon	21,800	28,000	NaK	43	1	44	65.9	5.12	71.1
Copper [illegible]	25,500	50KV	OS-124	18.5	25.5	44	86.0	8.4	94.3
Copper Silicon	24,750	50KV	OS-124	15.5	21.5	37	78.1	7.2	[illegible].5
Copper Silicon	20,500	50KV	OS-124	[illegible]	19	38	63.2	5.99	[illegible].2
Copper [illegible]	37,700	37,840	NaK	59	1	59	[illegible].5	6.01	[illegible]
Copper [illegible]	29,000	34,220	NaK	53	1	53	81.7	6.26	[illegible]
Copper [illegible]	28,400	28,[illegible]00	NaK	43	1	44	67.5	5.17	72.7
Co[illegible] Co[illegible]	[illegible]	74,400	NaK	120	1	121	187.5	14.35	201.9

Table 3. 2. 4-9. Cooling System Weights and Temperature For Various Transformer Designs

Conductor & Iron Type	5KV Total Losses Watts Qt.	10KV Total Losses Watts Qt.	Coolant	Coolant Fluid Temp. Rise	Convection Temp. Rise	Total Temp. Rise °C	Tube Wt. Pounds	Fluid Wt. Pounds	Total Cooling Weight
Copper Silicon *	22,000	23,500	OS-124	11.5	22.5	37	72.5	6.95	79.5
Copper Silicon *	16,950	22,000	OS-124	13.9	20.1	34	67.9	6.50	74.4
Copper Silicon *	14,100	21,170	OS-124	13.5	19.5	33	65.3	6.25	71.6
Copper Silicon ø	6,780	9,320	OS-124	5.9	9.1	15	28.8	2.76	31.6
Copper Silicon ø	7,500	7,800	OS-124	5	8.0	13	24.4	2.34	26.8
Copper Silicon ø	5,650	5,640	OS-124	3.5	5.5	9	17.5	1.67	19.2

* 5 Megawatt

ø 1 Megawatt

70 to 90°C. The temperature gradients can also be reduced by potting the transformer with a good heat conducting material. The additional weight of the potting material might be offset by overall system weight savings gained by higher coolant temperatures and/or a lower electro-magnetic weight with higher losses.

3.3 Power Transmission

Proximity Effect

A mathematical model for calculating the effect of close-spaced, three-phase transmission lines has yet to be developed. A method of calculating this effect was, however, derived in 1923 by H. B. Dwight.[1] While following his derivation, it was noted that one term was seemingly omitted which would appear to negate the derivation. His sample calculations, however, showed good correlation with previously calculated and measured proximity effect ratios for two-wire transmission lines.

A copy of one of his references has just been received which appears to be the basis for his derivation. When this article has been reviewed, his derivation may prove to be correct. Mr. Dwight's solution is obtained by solving iteratively a number of infinite series involving the dimensions of the three-phase lines. If the method is valid, the solution to these equations will be programmed for a digital computer for generation of the specified parametric data. The literature search is continuing at ASTIA for more references on the subject.

Because the transmission lines will probably be at high potentials, wide spacing for dielectric strength will be needed. The proximity effect would then be reduced greatly as pointed out in the First Quarterly Report. In addition, an approximation might be made using two-wire data to calculate the proximity effect. This should be pessimistic, because two-wire lines have less circum-

1. Dwight, H. B., "Proximity Effect in Wires and Thin Tubes", Page 850, AIEE Transactions, 1923

ference (180 degrees) exposed than the three-wire triangularly-spaced lines (240 degrees). With some error then, the equations developed and figure 3. 2. 5-10 in the first quarter report could be used to approximate the size and weight of the transmission line. The inductive effect can be neglected because the internal inductance, being very small in relation to the total (internal and external flux linkage) inductance, becomes even smaller as the lines are moved closer together.

Four-Wire Transmission

Because all conversion schemes in this study will be the full-wave type, no neutral or ground wire is needed. Four-wire calculations will not be considered any further.

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